

ABSTRACT

Title of Thesis: AN INVESTIGATION ON THE EFFECTS OF
FIREFIGHTER COUNTERFLOW AND HUMAN
BEHAVIOR IN A SIX-STORY BUILDING EVACUATION

Jessica Anne Kratchman, Master of Science, 2006

Thesis Directed By: Professor James Milke,
Department of Fire Protection Engineering

This study provides an investigation into the fundamental assumptions made in many current egress models and serves as a case-control investigation regarding stairwell evacuations. The evacuation of a six-story office building was filmed and observed. The introduction of two-directional travel within the same stairwell was considered: the upward direction of firefighters trying to get into the building, and the downward direction of occupants trying to get out. This provided conditions outside the assumptions generally made. Also an investigation into human behavioral patterns has been considered. The effects of these conditions have been analyzed both qualitatively and quantitatively. Results demonstrate that the higher a person entered the stairwell the more significant the effects of counterflow became. The wing with counterflow maintained more dense conditions throughout the duration of the evacuation. Behavioral patterns such as carrying objects, socializing, nonadaptive behaviors, and interaction with the firefighters were determined to have a significant influence on the population's performance.

AN INVESTIGATION ON THE EFFECTS OF FIREFIGHTER COUNTERFLOW
AND HUMAN BEHAVIOR IN A SIX-STORY BUILDING EVACUATION

By

Jessica Anne Kratchman

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Advisory Committee:
Professor James Milke, Chair/Advisor
Professor Andre Marshall
Professor Frederick Mowrer

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Dedication

Dedicated to the memory of

**Shera Alitt
1930- 2006**

**Gerald Alitt
1929-1999**

**Jack Kratchman
1929-2006**

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Chapter 1: Introduction

The demand for research-based, quantitative methods for predicting people movement in emergencies is ever increasing. Mainly, this is because of the recent shift in fire protection engineering towards performance-based design. Performance-based building codes generally focus on “establishing fire safety objectives and leaving the means for achieving the objectives to the design professional” [1]. In the case of emergency stairwell design, the stairwells must be able to accommodate an evacuating population. If there are no designated firefighter stairwells or elevators, as is often the case, then the stairwells should be able to accommodate the firefighters as well. Thus, there are more than just building components that make up the egress system. There are also a variety of complex human factors that need to be considered as well.

The effects of human behavior characteristics and decision-making in a building evacuation are investigated in this study in order to better characterize the fire safety needs of occupants and firefighters in a building. Also, the introduction of two-directional travel within the stairwell is considered: the upward direction of firefighters trying to get into the building, and the downward direction of occupants trying to get out. This multidirectional movement is referred to as *counterflow* (see Figure 1.1). In the last fifty years very few studies have been conducted on the issue of counterflow, and virtually none pertain to either stairwells, or emergency movement. Firefighter counterflow was present at the September 11, 2001, attacks on the World Trade Center. With such recent events, a need for getting occupants out of a building and firefighters into the building is even more relevant. Observations and quantitative analyses

characterize the movement of both the occupants and the firefighters in this study. In addition, a comparison to widely used models is provided.



Figure 1. 1 An example of counterflow

With a drive towards performance-based design it is necessary to understand and research the role that human behavior and decision-making have in building evacuations. However, since there is a limited amount of research regarding human behavior, and basically no research about firefighter counterflow in stairwells there is little understanding as to the degree to which these factors impact the outcome of an evacuation. Moreover, many research-based building evacuation models currently available are plagued by limited data, and out of date research. “Some traditional assumptions about people’s behavior in fires have even been shown to be erroneous by research” [2]. Thus, liberal assumptions are often made regarding the role that human response can have in the design of evacuation systems [2], and generally ignore completely the possibility of counterflow. If research-based models are implicated in performance-based designs, then it is essential that the models be based upon sound, ample, and current data.

This study serves as a case-control investigation about stairwell evacuations. The evacuation of a six-story office building was filmed and observed. The evacuation of two wings within the building was analyzed. In one stairwell firefighters were instructed to travel up the stairwell at different times throughout the evacuation. The other stairwell was the control stairwell with no planned counterflow. All 269 occupants and 6 firefighters that traveled in these two stairwells during the evacuation were analyzed and their individual movement characteristics determined.

In order to perform a thorough quantitative analysis, a series of egress parameters were determined for every evacuating occupant and every firefighter. The term *egress* is considered in this report to be the means and act of exiting. *People movement* is considered to be the characterization of a moving population. The opposing movement of *counterflow* presents a series of physical obstacles and decision-making needs to the population. The capabilities of occupants and firefighters to maneuver through the obstacles presented were determined. The basic egress parameters used in traditional people movement research are population speed, density, and flow rate. These parameters were determined for every person and for the population overall.

When considering each individual in the evacuation, it should be emphasized that no personal identities could be determined from the films and no record of any personal identities were provided to the researcher, nor could identities ever be determined based on the data (see Chapter 4 for a detailed discussion of balancing participant privacy with the need for tracking individuals).

Human behavior is defined in this report to be any observable response to external and internal stimuli. In the case of a stairwell evacuation internal stimuli are any

personal motivating experiences that drive individuals to respond and make decisions in particular ways. For example, being tired or feeling thirsty may drive an individual to decide to bring coffee with them during an evacuation. External stimuli are physical motivating factors usually in the form of barriers or obstacles that drive a particular individual to make particular decisions. *Physical capability* is considered the efficiency of a particular population given their abilities, as well as the physical restrictions within the stairwell as indicated in Figures 1.2 though 1.4. General human behavioral characteristics were considered. These include such actions as carrying of items through the evacuation, socializing with other evacuees, and specific reactions to the firefighters.



Figure 1. 2: Internal stimuli: example motivation to speak on cell phone



Figure 1. 3 Examples of external stimuli: objects blocking an exit path, or counterflow



Figure 1. 4 Examples of physical capability: personal physical ability, and the stairwell constraints

The objectives of this study are to provide a case-control investigation regarding counterflow versus no counterflow and to study human behavior in stairwell evacuations. Essential egress parameters such as speed, density, and flow were determined for every evacuating occupant and every firefighter. Human behavior characteristics were observed and quantified. The results obtained from this evacuation were compared to some of the traditional models used in people movement and egress modeling. The goal of this study is to add to the knowledge base regarding the human factors that are involved, and often overlooked in current egress modeling.

Chapter 2: Background

2.1 Introduction

This section examines the research currently available on human response to fire incidents. It also examines the current egress models and parameters used to predict emergency movement. The parameters that are considered by the literature to be the essential, basic parameters of evacuation movement are occupant speed, density, and flow rate. *Speed* is defined as the distance a moving person covers in a unit of time. *Density* is the number of people per unit area; it is a measure of how crowded an area is. *Flow rate* is the number of people that pass a reference point per unit of time [3]. This study also focuses on the presence of counterflow in evacuations. Counterflow is defined in this report as flow that is opposing the typical direction of movement; in the case of an evacuation the counterflow is the direction of travel opposing the exiting occupants.

2.2 People Movement and Stair Research

In general, many current evacuation models assume the following:

- “1. All persons will start to evacuate at the same instant.
 2. Occupant flow will not involve any interruptions caused by decisions of the others involved.
 3. All or most of the persons involved are free from disabilities that would significantly impede their ability to keep up with the movement of a group.”
- [3].

This general approach is referred to as the *hydraulic model*. Occupants are assumed to have little or no cognitive processes that could complicate evacuating. This style is a common approach followed and these assumptions are commonly used in practice.

With the above assumptions in mind, many building codes base their requirements on a unit-width or lane model [4]. These models assume that there is a linear relationship between evacuation flow and stair width. Since the occupants flow through the exit routes, then by increasing the width, flow is increased in a predictable, linear fashion. In 1955, Togawa of Japan published a study with such findings [4]. A 1935 study from the National Bureau of Standards (NBS) and a British study from 1952 also investigated this linear relationship [4]. Both the NBS and British study found a lack of empirical data available and recommended more research on the issue. Later, in 1958, the London Transit Board published a report that showed a linear relationship between crowd flow and stair width for widths over 1200 mm [4].

In the 1970's, Pauls conducted observational studies of building evacuation drills [4] from which the concept of an *effective width* emerged. Effective width accounts for the observation that occupants keep a small clearance from the edge of stairs or handrails, thus rendering the entire (or *clear*) width of the stairwell not used. Also during the 1970's, Fruin and Templer conducted research on both pedestrian movement and stair movement [5] [6]. Fruin provided linear formulas based on flow per foot of stair width, which subsequently is widely used [6].

The effective width model “relates the usable width of a stair and its flow capacity where there is a large simultaneous demand on an evacuation system by a crowd of people” [4]. Pauls derived this model by using films and video records of people in a

crowd walking through a stairwell. He plotted mean egress flow as a function of effective stair width per person. With his findings he created a relationship between the effective width, W (m), the number of persons evacuating, P , and the flow time, T (s).

Flow time is defined as the total time it takes the population to evacuate.

$$\frac{W}{P} = 8040T^{-1.37} \quad \text{Equation 2.1}$$

[4]

Using equation 2.1 and making specified adjustments, different stairwell conditions can be accounted for. For example, 1 percent is added to the width for every 5 mm that the riser exceeds 180 mm to account for a decreased level of “comfort, efficiency, and safety” associated with stairs having higher risers, or smaller treads [4]. Thus, although Pauls made the assertion that there is a direct, linear relationship between effective width and flow, he still accounts for certain stairwell conditions that may affect the performance of the population. Most of these conditions are regarding the ergonomics of stair movement.

In Nelson and Mowrer’s *Emergency Movement* chapter in The SFPE Handbook, using data reported by Pauls, they define speed as a function of the population density [3]. The theory is that at low densities people are capable of traveling at a speed determined by their physical capability and comfort. However, above a certain density all individuals are confined to move at the speed at which the crowd is traveling. If the population is less than the critical value of 0.54 persons per square meter, occupants are free to travel at their comfortable speed, independent of the speed of others around them. Above 3.8 persons per square meter the population cannot move at all [3]. Between these two values, speed is directly linked to density and based upon the equation below [3]:

$$S = k - akD$$

Where:

S = speed along the line of travel (m/s)

D = density (persons/m²)

k = constant (for typical 7.0-inch by 11-inch stairs $k = 1.08$)

$a = 0.266$ for speed in m/s and density in persons/m²

This correlation is based upon a regression analysis of the data in Pauls' study, which was conducted in 1980. In Pauls' study, he observed the uncontrolled total evacuation of tall office buildings. This correlation is also reported in Proulx's chapter in the SFPE Handbook, but it is simplified and put in terms of a 7 in x 11 in stair [2]. Proulx then reports flow rate as a function of population density, speed, and width. The model to determine flow rate is:

$$F = S \times D \times W_{eff}$$

Where:

F = flow (persons/s)

S = speed of movement (m/s)

D = density (persons/m²)

W_{eff} = effective width (m)

[2]

Fruin's 1971 model emphasizes the differences in age, sex, and ascent or descent in stair evacuations [6]. Therefore, from his findings he proposes a relationship between

speed and density, where a change in density could have affected the speed (and vice versa), but so could a change in the makeup of the population or the direction of travel. His data was not derived from direct observation of building evacuations; it is the tabulation of 700 surveys given to pedestrians. The following table summarizes the results of his study:

Table 2. 1 Pedestrian stair speeds reported by Fruin [6]

	Down Direction (m/s)	Up Direction (m/s)
AGE- 29 or younger		
Male	0.83	0.56
Female	0.59	0.54
Group Average	0.76	0.55
AGE- 30-50		
Male	0.69	0.51
Female	0.51	0.48
Group Average	0.65	0.50
AGE- Over 50		
Male	0.57	0.43
Female	0.47	0.39
Group Average	0.55	0.42
Average all sexes	0.67	0.51

Predtechenskii and Milinskii also developed a modeling tool to determine speed as a function of density. Their measurements show that “speed is a function of the density and the type of path” [7]. In this case, the type of path was a stairwell. They explain fluctuations in their speed data to be a result of changes in density, allowing people more or less freedom in movement. They did not address other issues such as human behavior in their model directly, but they did acknowledge that some situations have a “third factor, a psychological one, one which the speed of movement also

depends” [7]. Their model for movement on stairs is based on actual observations and “using mathematical statistics” [7], and is as follows:

Speed down stairs:

$$v_{down} = v \times m_{down} \quad \text{Equation 2.4}$$

Where:

$$m_{down} = 0.77 + (0.44e^{(-0.39D)})(-0.39D)\sin(5.61D - 0.224) \quad \text{Equation 2.5}$$

$$v = 112D^4 - 380D^3 + 434D^2 - 217D + 57 \quad \text{Equation 2.6}$$

The value m_{down} is the number of the median interval. The interval for density is between 0 and 0.92 m²/m². Density is defined in this calculation as the sum of the area of horizontal projections that *all* of the individuals take up in the area of interest [7].

Meaning, density is the sum of the area occupied by each person in the space.

Density:

$$D = \frac{\sum f}{\delta l}, (\text{m}^2/\text{m}^2) \quad \text{Equation 2.7}$$

Where:

f = is the area of horizontal projection for each person, (m²)

δl = area, (m²)

[7]

Predtechenskii and Milinskii provide different f values based on different considerations that define the area one individual occupies. For instance, whether the

occupants are adults or children, or if they are wearing summer or winter clothing could change the occupied area of the individual.

Predtechenskii and Milinskii also examine a third term that is the product of speed and density. They refer to this term as *intensity of movement* [7]. Intensity of movement is in terms of meters per minute and “characterizes the kinematics of the process of foot traffic flow” [7]. Their measurements are based on observations of non-emergency movement in a variety of different scenarios. To evaluate speed and density they choose a segment of path and a part of the flow width and length. Then the observer stood at the end of the segment along the direction of flow. Using one “conspicuous person” [7] in the flow, the observer noted the time that the person entered the segment and counted the people passing him/her. When the person passed the observer at the end of the segment, counting ended and the time was recorded. Consequently, the number of people in the segment was used to calculate density, and the duration of movement through the segment to find speed. [7]

In the 1980's Kagawa, Kose, and Morishita of the Building Research Institute in Japan considered a more complicated element of stairwell movement, they considered the behavior of people as a component of movement [8]. Their observations were determined through the video recording of a simulated fire evacuation in a high-rise office building in Tokyo, and a questionnaire survey completed by evacuees afterwards. They were particularly interested in the flow conditions of the stairwells and in the mixing conditions that occurred when evacuees entered the stairwell from different floors. The video cameras were setup in groups of four at the entrance doors to the stairwell. Several cameras were also placed in the stairwell to monitor general flow of

people during the simulation. Only one stairwell was observed because of a shortage of equipment. The results showed that the first evacuees (considered as occupants who may have entered at the third floor) came out of the stairwell 42 s after alarm initiation [8]. For all evacuees of the 53-story building to exit, it took approximately 16 minutes [8].

One major difference between Kagawa, Kose, and Morishita's study and the one conducted in this report is that in this report each person is individually tracked through the stairwell. This provides an increased level of detail. Kagawa, Kose, and Morishita noted that in their study, even though only about a fifth of the occupants participated in the study, there were cases of stagnation, slowing, and even stoppages within the stairwell [8]. On their questionnaires, occupants noted that they felt the stairwells were too narrow, even though there was in general only one occupant per stair. One might assume that stagnation occurred with higher densities, but the occupants and researchers rarely observed high density even during stagnation [8]. The average speed was estimated to be between 16 and 20 s per floor, with a floor height of 3650 mm, and the stairwell width 1200 mm. This reflects the range of movement expected by the researchers from unobstructed to crowded. [8]

There were cases in their study where occupants were noted to stop for 10 to 15 s to wait for congestion to clear, and the researchers concluded, "it is highly probable from the present result that a standstill in the stair may appear if 3 or 4 neighboring floors were simultaneously evacuated. From this point of view the stair width is clearly insufficient" [8]. This simulated evacuation was performed with no planned opposed flow, and no planned obstructions. This begs the question as to whether stairwell design that primarily

considers only a linear relationship is adequately considering all the conditions experienced in an emergency stairwell.

Frantzich performed a similar filmed evacuation with Lund University in Sweden [9]. The purpose of this study was to derive data on walking velocities and walking patterns on stairs during an evacuation, specifically during upward movement and on different types of stair designs, such as spiral stairs. Frantzich purposed that analytical methods of stairwell design should regard the time an evacuation process takes in terms of three phases [9]:

1. Awareness or detection (t_a)
2. Behavior and response (t_b)
3. Movement (t_m)

The sum of these times should be less then the time it takes for a critical situation to arise (t_{crit}):

$$t_a + t_b + t_m < t_{crit} \quad \text{Equation 2.8}$$

The current study focuses on movement time (t_m) on the stairwell component. The test subjects in Frantzich's study were between 20-30 year old college students, and the setting of the tests was described as "controlled laboratory experiments" [9]. The mean velocity determined for upward movement on straight stairs was 0.55 m/s, and for downward movement 0.7 m/s was the mean velocity. For upward movement on spiral stairs the mean velocity was determined to be 0.55 m/s. Thus, the difference between the types of upward movement performed on spiral stairs versus straight stairs did not affect the mean speed of the test subjects. The density of the population is described in terms of

interperson distance between participants (i.e. the more distance between people the lower the density, and the less distance between people the higher the density). For stairwells that are described as both wide and narrow he found little correlation between interperson distance and velocity in downward stair movement (unless it was so dense that people could not move). Frantzich did note however, that this study focused on persons moving in one direction only, and on staircases only, and “another situation of interest is to study the change in movement pattern as one or more persons are moving in the opposite direction of that of the main stream ” [9]. He noted that this could be a “common occurrence” [9] when “firefighters are entering the building at the same time as people are evacuating” [9]. Frantzich found this an important case study because “some information indicates that the flow of people will decrease to half” [9].

With more than two million disabling stair accidents and about 4000 deaths from stair accidents each year in the United States, stairwell design is an extremely important component of egress, even in non-emergency situations [10]. Research conducted at the Building Research Establishment in Britain on stairwell safety concluded, “the actual building conditions are often very different than what is envisaged in the building regulations” [10]. This research was based upon data from a national data collection system for accidents and from interviews at the sites of home accidents. It is important that research continue to be conducted about stairwell design that not only links essential parameters such as flow and stairwell width, but also that considers the conditions that are presented in the stairwell to the evacuees, and the behaviors that may be induced by certain obstacles. Once an understanding of how the conditions inside a stairwell affect movement patterns, then if it is deemed necessary the stairwell design can be adjusted to

accommodate. For example, Pauls noted a better tread size as a means to reduce stairwell accidents and improve safety in descent [10].

2.3 Pre-Movement Time

With the fire protection industry moving towards performance-based designs it is essential to be able to predict the time required for occupants to reach safety. Therefore occupant evacuation models are likely to become an even more important tool than they already are. It is essential that these models are based upon sound data or else the design of stairwells will be based on models that do not accurately predict how people will move in a variety of situations. According to a study conducted at the National Research Council of Canada by Proulx “while most models can usually reproduce the space geometry (i.e. the lengths and width of corridors and stairs), variables related to the occupants themselves are often ignored” [11]. With this in mind it is important to consider the conditions and behaviors inside the stairwell and also the amount of time it takes people to decide to evacuate. This time is called *pre-movement* time. It encompasses all the delay time before occupants begin to evacuate. This could include such activities, in an office building, as gathering valuables, putting a coat on, and notifying others. It also includes the time it takes for a person to recognize a problem and decide what action, if any, to take. [11]

There are six perceptual processes that are considered critical in recognizing a fire [12]. Because of the rapidly changing nature of informational cues in a fire, the entire perceptual process can occur in a matter of seconds [12]. However, the process can be considered subject to the ambiguity and amount of fire cues present, as well as social and

cultural conditions. Being in a social group also is observed to affect one's reaction to emergency stimuli. "The recognition of ambiguous fire incident cues as indicators of a possible emergency condition appears to be inhibited by the presence of other persons." [12]. Latane and Darley investigated the inhibition of adaptive behaviors by studying the reaction of college students to an emergency situation [13]. Since the occupants of the current study were in social groups imposed by an office scenario, it is possible that their reactions to the fire drill were inhibited by the presence of others [13].

In her study Proulx found the pre-evacuation time was significant enough that it should be included and considered in models. In residential facilities with alarms that the occupants characterized as "good" meaning they were audible, the pre-movement time was 2:49 minutes [11]. In residential facilities with alarms characterized as "poor", meaning they were harder to hear, the pre-movement time was 8:35 minutes [11]. In the office buildings observed, between 0:36 minutes and 1:03 minutes were determined to be the pre-movement times experienced [11]. The office buildings all had alarms considered by the occupants to be "good." This is primarily because the open floor plan of the offices, which accounted for better audibility, and a greater view of others to decide what to do in the situation. Also, the office building had smaller times because the pre-movement activities were less time consuming. In residential facilities occupants reported more activities such as gathering family members, helping activities, and notifying others than those in the office building. This pre-movement time varied from lengthy to short, but it should be considered in models that are used for stairwell design since it can be a determining factor. [11]

There are also serious behaviors that have been observed and are considered nonadaptive. While these behaviors are generally rare, they can occur [12]. These are behaviors that are self-deprecating, and inhibit others or one self from reacting safely or performing productive behaviors [12]. Nonadaptive behaviors are responses such as flight, or panic type behaviors and “appear to be an infrequent, unusual, or unique participant behavioral response in most fire incidents” [12]. These behaviors can occur at any point in the pre-movement or movement phase of an evacuation.

The complex movement patterns inside the stairwell are also needed to make a complete model. There have been major strides in understanding and researching people movement in evacuations. However, human behavior is often simplified or not included in the predictive models at all. One problem is that “most egress rules were developed in their present form some twenty years before research was done” [14]. There is also a limited amount research available. In fact, “some traditional assumptions about people’s behavior in fires have been shown to be erroneous by research especially that conducted during the last three decades” [2]. The modest amount of research that even exists is often dated. Cultural and behavioral norms can shift with time. Even average body sizes can change. With the limited nature of the data, often evacuation models are lacking understanding of the complex relationships that may exist between the essential egress inputs simply because not enough exist. It needs to be emphasized that there are “limitations in the quantitative methods currently available for people’s movement in buildings” [2].

2.4 Human Ergonomics on Stairs

Once an individual commits to evacuating, there are physical restrictions imposed on the human body. Behavioral responses to a fire are subject to psychological limitations, but movement itself can often be subject to physical limitations. Movement on stairs consumes ten to fifteen times more energy than walking an equivalent level path [5]. The actual motion of walking is also much different than climbing or descending stairs. Unlike walking, the center of gravity for the body is transferred forward. “The front leg is lifted and placed on the first step to support the body and to prevent it from falling forward. Both the front and the rear legs provide the push off... The rear leg is then lifted and swung forward and placed on the second step, and the cycle is repeated” [5].

When descending stairs one’s “center of gravity must be held backward because of the increased danger in falling” [5]. Descending stairs requires greater concentration and control, and thus is a greater expense of energy. Climbing or descending stairs both require a “more acute cone of vision for more accurate foot placement, and to avoid tripping” than such movements as walking. Locomotion on stairs is more constrained because of the boundaries imposed by the stair tread and riser configuration [5]. During unimpeded movement, an increase in walking speed can be achieved by increasing pacing rate and space between each step. In stairs however, the pacing is predetermined for everyone. Thus, an individual’s natural stride cannot be used on stairs.

2.5 Counterflow

As stated earlier, counterflow is movement that opposes the general direction of flow. In the case of a high-rise evacuation, the general direction of flow is down the

stairwell and toward the exterior of the building or to a protected area. More generalized terms for counterflow are two-directional flow, multidirectional flow, bi-directional flow, or opposed flow. Although the models presented in this chapter are commonly used in engineering practice there is no emphasis or mention of the possibility of counterflow, or its effects on one-directional flow. Largely, this is because of a lack of data regarding its effects. Since flow, speed, and density are all assumed by most models to be intimately linked, then counterflow has the potential to complicate the models. There are only a few notable studies on the issue, and most of them do not pertain to emergency movement. Navin and Wheeler studied pedestrian flow characteristics on sidewalks “under various counterflows” [15]. Their hypothesis is that “the percentage of flux in one direction would affect the speed and reduce flow under conditions of counterflow” [15].

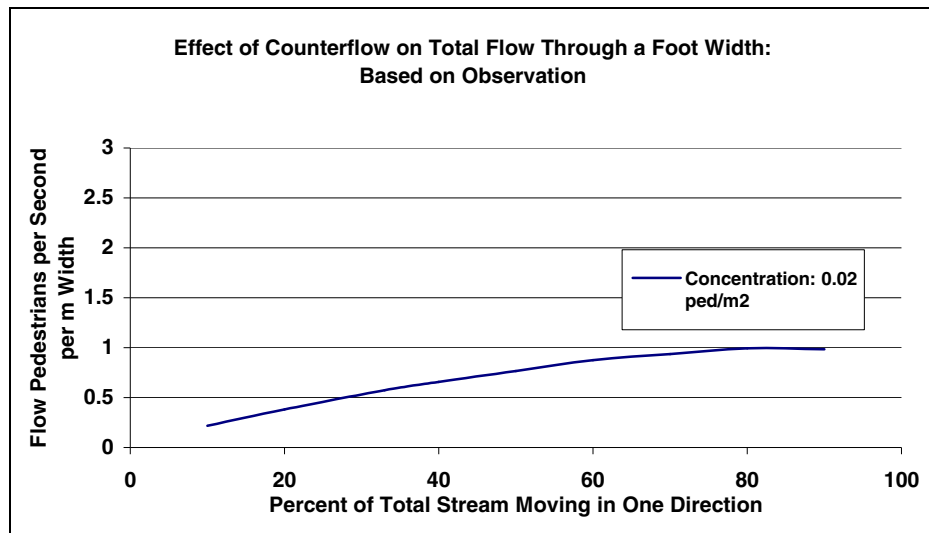


Figure 2. 1 Results from Navin and Wheeler’s study (in terms of clear width)

Figure 2.1 is a graph of Navin and Wheeler’s observed results. Flow is presented as a function of the percent of the total stream moving in one direction. Therefore, as a

larger percent of the population was moving in the same direction, flow increases. The more counterflow there was, the more flow is observed to decrease. Furthermore, the researchers report that in the flow conditions that were entirely one-directional, where no counterflow was ever experienced, pedestrians were observed to move at approximately 1.37 pedestrians/s-m, which is greater than the pedestrians observed in counterflow conditions ever achieved (see Figure 2.1). This suggests that a population exposed to significant counterflow conditions can have lingering effects even after all the counterflow is eliminated. [15]

Others have considered that the issue of counterflow may complicate an evacuation but with little empirical data available, considerations are often in the form of a safety factor, or extra travel space. Fruin, Templer, and Pauls have addressed the issue of minimum stair widths for “situations where stairs are heavily used by crowds for unidirectional, or bi-directional flows” [4]. Fruin recommends, based on “his belief” [6] that a 760 mm lane should be provided for single directional flow, and a 1520 mm stair width should be provided “particularly in situations where bi-directional flow occurs on stairs” [6]. Fruin also emphasizes that enough space should be provided to people who are carrying items such as luggage in the stairwell [6]. Templer suggests that stairs should be wide enough for people to travel side by side or pass with comfort. The consensus among the research is that the traditional minimum width “is much too narrow for extensive unidirectional or bi-directional flow” [5].

At the University of Canterbury in New Zealand, Holmberg investigated opposed flow movement in corridors. Test subjects were instructed to walk along a corridor while one or more people walked in the opposite direction of the main flow. The densities of

people in the study varied from low to high. Observations were made “to see how subjects change their direction when confronted with another person approaching from the opposite direction” [16] and whether or not their “movement velocity is effected while the other person is passing” [16]. This was studied using video analysis of the pedestrians. The results showed that the more people opposing the major flow, speed was reported to be slightly slower (by about 0.2 m/s). This is in agreement with Navin and Wheeler’s results. The group that experienced the larger number of people opposing the major flow also experienced greater densities when traveling through the corridor.

2.6 Fire Drill Experiments

When studying human behavior in fire, real emergency data is most desirable and will provide the most realistic predictor of future behavior. However, it is not as readily available and the timing is not as easy to predict as a fire drill. As a result, for practical purposes, fire drill data is often used to study emergency behavior. A key assumption based on much of the current research available is that fire drill data can be used to approximate the response of individuals in an actual emergency [2]. This is, of course, subject to the proximity of the population to the hazard; meaning that fire drill data best approximates the reaction and conditions experienced of those who are not close enough to the hazard to positively identify it as an emergency. In a high-rise evacuation, as is the case in this study, it is conceivable that a significant portion of the population has not been exposed to enough fire cues to be certain if it is an emergency.

Individuals in emergencies are observed to be optimistic and reasonable, and panic very rarely [2]. This is especially true with limited or ambiguous amounts of fire

cues at the initial stages of the fire. In a large building it is realistic to assume that there could be occupants that may need to be evacuated that have not had enough fire cues to recognize and trust that an emergency has occurred. Furthermore, in real fire emergencies if individuals do not have an abundant amount of information they are observed to assume that it is not a real emergency [2]. The decisions and behaviors “derived from careful documentation of realistic evacuation drills, is a good basis for developing guidelines for the design and use of emergency egress systems” [2]. Although this is not ideal, it is some times the most practical option.

It should be emphasized though, that fire drill data is often used as a *predictor* of emergency movement. It is by no means assumed to be as reliable as real data from an actual emergency. Fire drill data often serves as a realistic and practical substitute, and must be considered idealized in nature. After all, problems that occur during normal building use “will tend to exacerbate situations in emergencies” [2]. This includes many well-known fire protection issues such as “faulty communication, circulation hazards, and way finding problems” [2]. As such, caution needs to be exercised in the use of drill data.

Chapter 3: Approach

3.1 Introduction

By strategically positioning cameras so that occupant and population movement can be accurately tracked, this experiment expects to gain insight into the effect of human behavior and firefighter counterflow on movement characteristics. This section describes the approach used to observe the movement and behavior of evacuating occupants and ascending firefighters.

3.2 The Building

For security purposes, and to protect the wishes of the building owners, a map of the entire building is not provided, nor is the identity or location of the facility. However, this section provides a detailed description of all relevant features of the building for this analysis.

The building studied was a six-story, high-rise office building with seven wings. Each wing is shaped like a large rectangle. The lengths of the wings are all adjoining and parallel to each other, forming an even larger rectangle. During the drill, evacuation from two stairwells was observed. The stairwells were in separate, neighboring wings. The wings observed were mirror images of each other, with the same number of elevators, stairwells, and exterior exit doors. The stairwells in each wing were equally accessible from all rooms and floors. Both stairwells deposited occupants into a lobby through a set of double doors. After traveling through the lobby, occupants traveled down a small set of steps to a protected vestibule. The vestibule then led to the exterior of the building. The building owners plan fire drills regularly twice a year. The exact dates of the drills

however are not divulged to the occupants. In this report mid-landings are numbered in terms of half floors, and the notation of 'F' followed by a number denotes the different floor levels.

3.3 Travel Path

The dashed lines in Figure 3.1 describe the average travel path of non-merging occupants through Wing A. The method used to determine this path is discussed later in this section. Individuals that have entered into the stairwell and are assimilating into the stream of already evacuating occupants are considered to be *merging* occupants. Their travel path is discussed later in this section. Wing A served as the control wing. No firefighters were sent up this wing, thus no counterflow was planned.

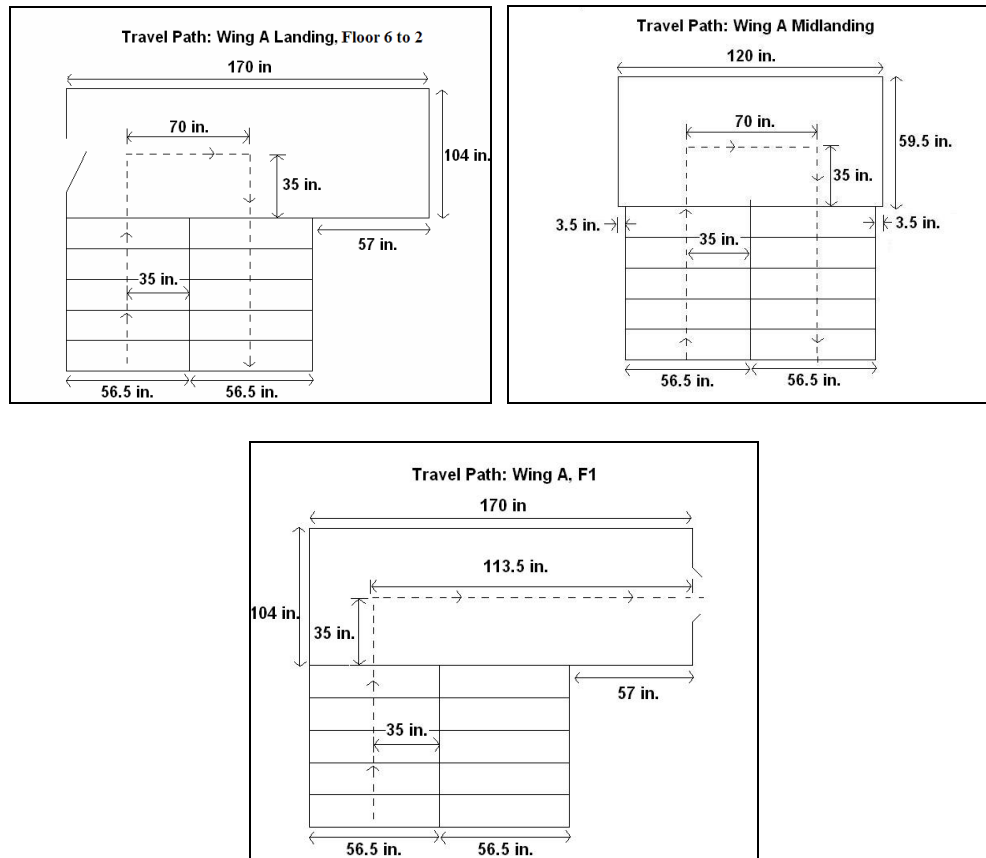


Figure 3. 1 Wing A travel path (dashed lines), all doors 36 in

The next set of diagrams in Figure 3.2 describes Wing B landings and mid-landings. As with Wing A, the dashed lines represent the travel paths of non-merging occupants. Wing B served as the variable wing where firefighters created counterflow for exiting occupants.

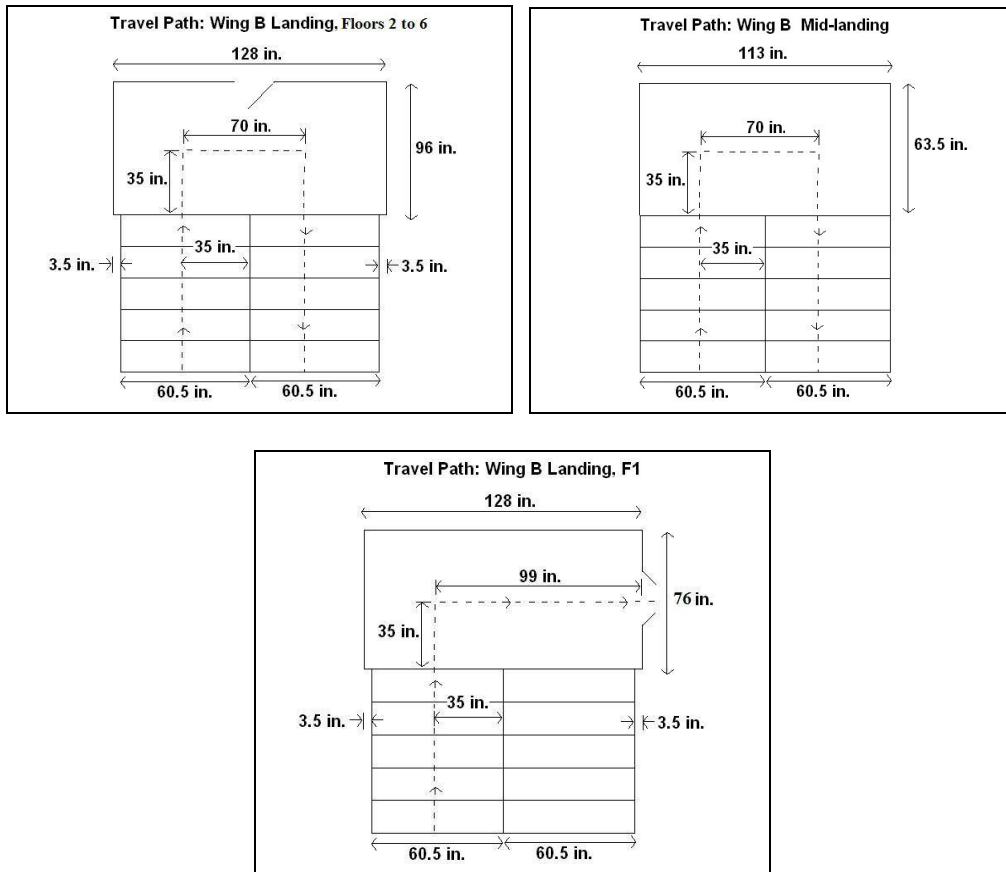


Figure 3. 2 Wing B travel path (dashed lines), all doors 34 in

In Wing A, all doorways were 36 in wide, and in Wing B all doorways were 34 in wide. All stairwells had hand railings. There was also natural lighting from windows and artificial lighting from fluorescent, wall-mounted lights. The travel paths in both wings were the same from the sixth through the second floors, even though the landings in Wing A were larger. This is because the extra area on the Wing A landings were accounted for in a 57 in cutout that was not used for travel. This cutout was primarily used to store the evacuation chair, and contained a large window (see figure 3.3).



Figure 3. 3 Wing A, 57 in cutout used to store evacuation chair

Another difference in the two stairwells was the door location in F6 through F2 (see Figures 3.1 and 3.2). This made comparing merging flow in each stairwell not viable, since it would have been unclear what to attribute any differences to. Due to this difference and issues with camera positioning (discussed later) merging flow is not considered in great depth in this study; this report primarily discusses movement once an occupant has merged into traffic. Once merging occurred, the travel paths in both wings were the same and could be compared. Further details regarding the analysis method to account for the discrepancy in door location, and any differences it may cause are described in detail in Chapter 4.

The widths of the stairs themselves were also different in both wings. The stairs in Wing A were 56.5 in wide, and Wing B was 60.5 in wide. This was dealt with by assigning the variable wing (i.e. Wing B) as the wider stairwell. In the variable wing there was firefighter counterflow. Wing B was selected as the stair for counterflow assuming that the effect of counterflow was less on a wider stair than a narrow stair.

This report defines the travel path for the occupants as the path traveled on the stairwell in the middle of two occupants traveling abreast. This is intended to be the average path taken down the stairs by the occupants. It is predicted that in this drill two occupants could comfortably travel abreast because the stairwells were wide. Often egress models that predict single-file movement down stairs use the middle of the individual's body as the travel path. Thus, this study uses the middle between the two occupants as the travel path. Therefore, one person was predicted to be traveling in an inner lane closer to the handrail, and one in an outer lane farther away. Logically, the outer lane was a longer travel path, and the inner lane shorter. It should be stressed that this is an estimate for travel path and used for comparison between the wings and to existing egress models. Occupants traveling in the inner traffic lane were predicted to travel 13 inches from the handrail, and the outer edge of the handrail was 5 inches from the edge of the stairs. To establish an average body width for occupants in this drill, objects in the film of known sizes were compared to occupants. The average body width of a person in this drill was estimated to be 17 inches. Therefore two people traveling abreast, in this drill, were approximately 34 inches (assuming there was no space between the individuals). If the individuals were traveling in the predicted pattern of two abreast, then the line in the middle of the two people who traveled side by side is 35 inches from the edge of the stairs (see to Figure 3.4).

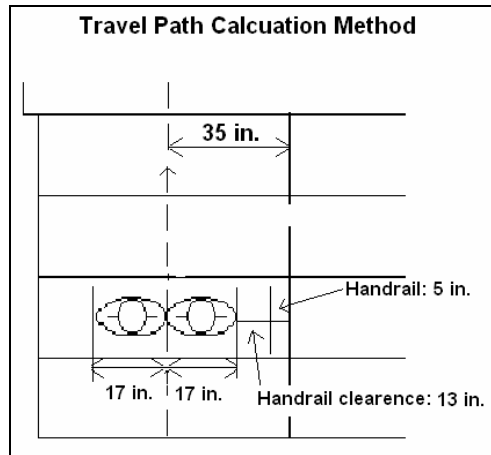


Figure 3. 4 Method to determine occupant travel path

To determine the travel path for the firefighters, a similar approach was used. Unlike the occupants, every firefighter in this drill traveled single-file, since this was how they choose to travel. Thus, their travel path was estimated as the center of one of their body widths. One firefighter was estimated, in this drill, to have a width of 30 inches, completely geared and equipment on his person. He was also estimated to be standing 15 inches away from the handrail, and the outer edge of the handrail was 5 inches from the edge of the stairs. As with the occupants, the average body width of the firefighters was determined by comparing their body widths to objects of known sizes in the films. They were estimated to be standing further from the handrail than the occupants; since their width is predicted to be larger it would follow their stance would also be wider, and thus their bodies positioned slightly further from the handrail (see Figure 3.5).

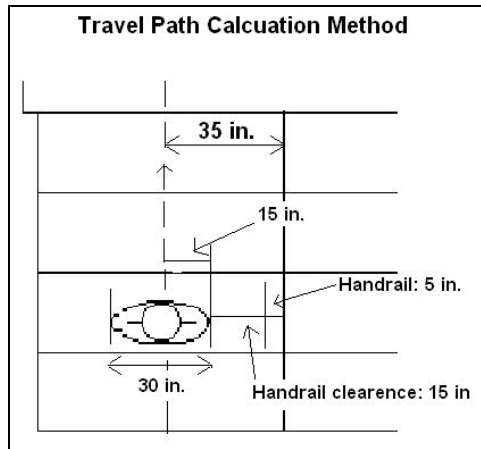


Figure 3.4: Breakdown of travel path determination for firefighters

In both wings there were eight steps per flight. The only exception was in Wing B between F2 and F1. From F2 to F1.5 there were six steps, and from F1.5 and F1 there were 10 steps; this averages out to eight steps for each flight. The steps in both wings had the same tread and depth dimensions. The depth of each stair was 8 inches, and the tread was 11.125 inches. The diagonal distance of each stair was 13.7 in.

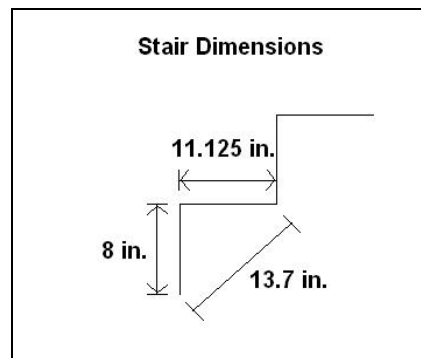


Figure 3. 5 Stair tread, depth, and diagonal dimensions

There were eight steps, or nine vertical drops, from mid-landing to landing, and landing to mid-landing. Since the diagonal distance per drop was 13.7 inches, and there were nine vertical drops per flight, the diagonal distance for each staircase of eight stairs was 123.3 inches. The two flights in Wing B that had a different number of stairs were accounted for as well. In Wing B, the landing on F1 was also different then the rest of

the landings in that wing. The landing on F1 was 128 inches by 76 inches, as opposed to the typical 128 inches by 96 inches.

3.4 Firefighter Makeup

The firefighters that participated in this drill were from the jurisdiction local to this office building. Two groups were sent up, with three firefighters per group. As stated previously, each firefighter traveled single-file up the stairwell and exited at F5. An engine company was the first group to travel up the stairs, and the second group was a truck company. Each member was fully geared with equipment typical of high-rise firefighting. The lead firefighter in each group had a white helmet and the other two had black helmets. The leader of the engine company was equipped with a self-contained breathing apparatus (SCBA) on his back, flashlight, mask, and radio. Additionally the two other members also had what is known as a “high-rise pack” [17]; this contains attack lines, fittings, nozzles, etc. Group 2, the engine company, each had a SCBA, flashlight, mask, and radio. The second member of this group also was carrying an axe. All firefighters in both groups were male.



Figure 3. 6 Firefighters ascended the stairwell fully geared

3.5 Occupant Makeup

The occupants of this building were an able-bodied, non-resident population. The drill was performed in the morning, and in the summer. The time of day and season play a role in what occupants may be carrying (i.e. coffee mugs, newspapers, etc), and what occupants could be wearing (i.e. winter coat versus no coat). The population had varying diversity and backgrounds, as well as mixed gender, body type, physical ability, and age. The age of the occupants ranged from between 18 to 65, and there were no children, elderly, or infirmed occupants observed. There was one visually impaired occupant who traveled with an evacuation buddy in Wing A. He is not considered handicapped in this report because he did not need an evacuation chair to evacuate, nor was his ability to evacuate impaired by his handicap. In Wing A, 128 occupants exited in total. In Wing B, 141 occupants exited, as well as six firefighters in total. Wing A had 40 men, and 88 women; Wing B had 94 men, and 53 women. Thus a total of 269 occupants and six firefighters traversed the stairwells in this evacuation. There were floor wardens and security guards in both wings, but they only sporadically held doors open for occupants, and generally stood out of the way of movement.



Figure 3. 7 Occupant makeup was mixed gender, age, ability, and body type

3.6 Experimental Setup

Effective camera positioning was essential to the successful outcome of this study. Digital video cameras were positioned throughout the stairwells. Wall-mounted cameras were situated to view the F2, F3, and F5 landings in both wings. Additionally, Wing B had a view of the F1 landing, as well as a camera facing the exterior exit doors from the inside. In Wing A, there was also a tri-pod camera facing the exterior exit of the building. Both wings also had a tripod camera facing the double door exit of the stairwell. In this experiment the number of camera views were only limited by the availability of cameras. There simply were not enough cameras to be placed at every floor. Figure 3.8 provides a layout of the cameras and camera views (the solid boxes are camera locations with a cone of vision and the X is the tripod camera), and Figure 3.9-3.11 provides views through each type of camera.

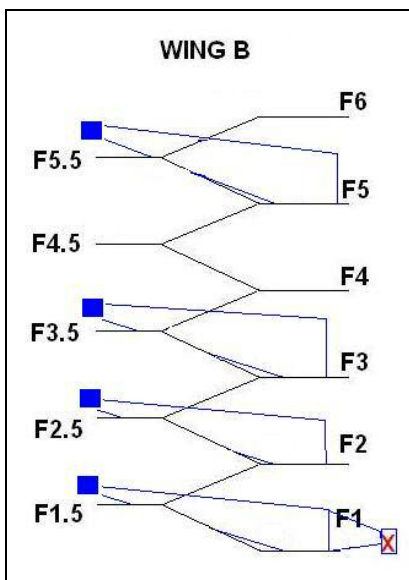
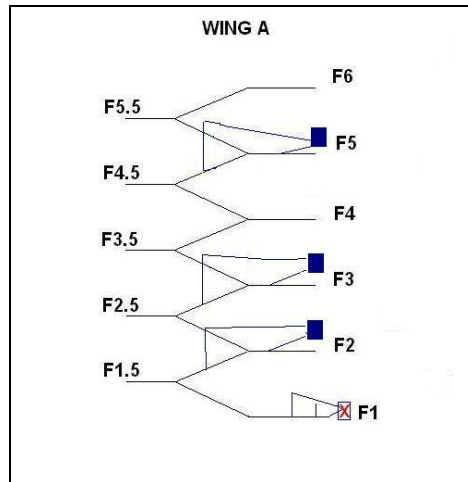


Figure 3. 8 Camera locations and cones of vision

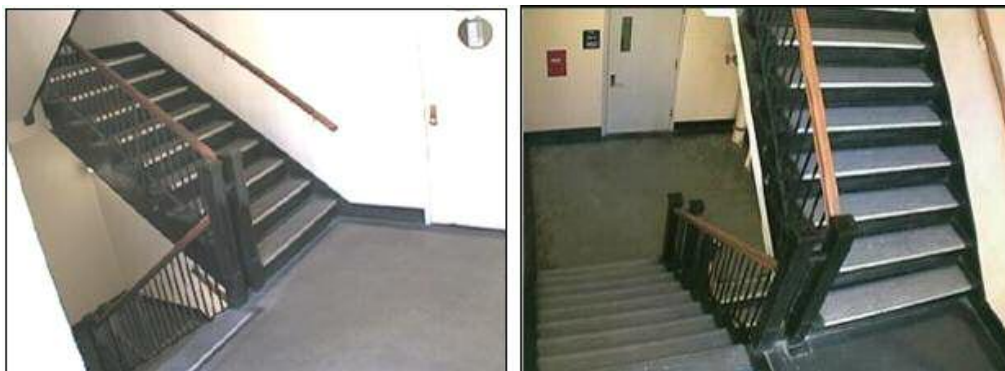


Figure 3. 9 Wing A (left), and Wing B (right) wall-mounted lobby camera angles



Figure 3. 10 Wing A (left), and Wing B (right) double door tri-pod camera angles



Figure 3. 11 Wing B exterior exit tri-pod camera view

The apparatus used to mount the cameras inside the stairwell walls consisted of three metal rods bolted together. The horizontal rod was bolted to the camera and affixed such that it could rotate the camera up and down. This allowed for slight adjustments of the camera angle. The apparatus was attached to the windowsills using a standard clamp (see Figure 3.12). Also, standard tripod cameras were used to view of the double doors, and the exterior of the building.



Figure 3. 12 Wall-mounted camera apparatus

Due to the geometry of the stairwells, cameras were positioned slightly differently in the two wings in order to try and get a full view of each landing. Recall that Wing A had a 57 in cutout with a large window, which was not in the travel path. This window served as a perfect location to mount the cameras. It provided a complete view of both sides of the stairwell (i.e. the side where people came from the floor above, and the side where people continued to the floor below), and the entire part of the landing used in travel (see Figure 3.8). In Wing B, however, there was no such cutout. As a result, in order to obtain a full view of the entire landing, the cameras were positioned one mid-landing above, and pointed at the landing below (see Figure 3.8 for the difference in camera placement and cones of vision between the two wings are provided).

Unfortunately, it became clear upon analysis of the films that it was much more important to have a complete view of both sides of the stairwell, and not necessarily the entire landing. At every landing camera there were two ways an occupant could enter the view. They could have either entered the stairwell from a floor above, or merged into traffic at that particular camera. Of course, some of the occupants who merged from

above also may have merged into traffic from a floor not filmed. Since merging data could not be obtained for everyone but stairwell travel could have been, and the camera angles were limited in Wing B, getting an entire view of the landing made less sense than getting an entire view of the stairwell, where all the occupants, in both wings, traveled in the same manner.

By having positioned the camera a half floor up in Wing B, in order to optimize the camera view of the landing, the clarity of the occupants in the films on the landing below degraded greatly, this made it impossible to track individuals at these landings as they entered. The poor camera angle in Wing B also obstructed the view of part of the stairwell, which made tracking inside the stairwells at the landings difficult. An analysis method to compensate for these camera angles is detailed in Chapter 4.

3.7 Procedure

Filming of the evacuation took place on June 1, 2005. The drill was held on a sunny, warm, and clear day. All cameras were set up and positioned prior to the alarm sounding. A week before the drill occurred camera angles were reviewed, and all the mounting devices were tested. On the day of the drill, all cameras were turned on simultaneously at 9:30 am. At 9:47 am the fire alarm was activated. Then, at 9:48 am the first group of firefighters was sent up the Wing B stairwell, and at 9:49am the second group was sent up. Time 00:00 minutes in the films are when the alarm is activated.¹ The procedure was performed so that all the cameras were synchronized, as well as the actions of the groups operating the cameras in each stairwell. Walkie-talkies were used

¹ From this point forward in the report time will be relative to the activation of the alarm.

to further facilitate the synchronized nature of filming, by allowing the camera operators in both stairwells to communicate.

Chapter 4: Data Analysis

4.1 Introduction

The objective of this chapter is to develop an accurate way to distinguish and follow all 269 occupants and six firefighters as they evacuated through the two stairwells, and to be able to use these results to calculate the basic egress parameters.

4.2 Participant Privacy

Great lengths were taken to protect the identity of all individuals filmed. Cameras were ONLY placed in public areas, i.e. public stairwells. There was no identifying information on any film regarding the specific address or location of the particular building. All cameras were placed a sufficient distance away so that information obtained was ambiguous and could not have been used to identify anyone personally. The quality of the films was also a poor resolution so that personal identities were concealed. Information such as male versus female, tall stature versus short, skirt versus dress, etc. was used to identify occupants from one and other, but not to identify them personally. There is absolutely no link to personal names or identities, and no factor could be identified directly or through identifiers linked through the subject.

Since the personal identity of occupants was not important to this study it was not the intention of this study to in any way collect information that could have led to their identification. It was the overall capabilities of the population that was of interest. Furthermore, no subjects were actively recruited. The building owners invited the research team to film their facility and to conduct this study, since evacuation efficiency is of importance to their occupants' well being. The firefighters involved in the study

were informed before the experiment. Again, no personal identity of these individuals could have been determined from the films since the films were of too poor quality to distinguish such personal identifying details.

There were no risks to the subjects involved in this study. Fire drill such as the one filmed are planned by the building owners and occur periodically throughout the year, so the risks imposed from the fire drill itself would have been present with or without the presence of the cameras. Furthermore, since filming was done in such a way as to protect all personal identities there was no personal risk posed to the subjects by being filmed.

Adequate provisions were made to protect the privacy of subjects and to maintain the confidentiality of information. Data was stored on one set of compact discs during analysis, with only the researcher having access to the films during the study. The original cassette tapes from the camcorder were destroyed directly after they were converted into digital format. The films were held at a safe location during research. Once the analysis portion of the research was concluded, the tapes were completely destroyed.

4.3 Video Editing

The analysis began with the raw footage of the filmed evacuation. The footage from the camcorders needed to be saved from the camcorder to a CD, as well as edited to make the data analysis more efficient. Recall from Chapter 3 that all cameras were turned on approximately 14 minutes before the alarm activation. This was done to ensure that all of the devices were properly functioning, and so that all cameras were focused directly on the locations of interest. Since this footage did not pertain to the experiment,

it was eliminated up until the second the alarm sounds. This way, time 00:00 minutes on every film was the moment the alarm was activated and all the films were in sync with each other. It was also necessary to perform such operations as lightening any footage that was too dark to analyze. Thus, software was needed that could convert and save the films to a compact disc, and edit and cut the raw footage where needed.

Adobe Premiere Video Editing Software was the program of choice for the preparation of the films. Among other capabilities this program is equipped to perform all the operations needed to prepare the films for data analysis. MiniDV devices, or *mini-digital-video devices*, were used to film this evacuation. These devices record footage onto small cassette tapes. The device can be linked to a personal computer using an IEEE 1394 (Fire Wire/I-link) DV interface. The films can subsequently be viewed on a PC using this interface. A DV codec was used to compress and capture video (a codec is a compression scheme²). The films were standard video (4:3 interlaced), and the audio was 32 kHz (12/16 bit). Drop-frame time code numbering and real-time preview was enabled when Adobe Premiere was opened. Real-time previews allow the user to immediately preview a film with any edits.

The first step in the editing process was to capture the films onto the PC so they could be viewed in Adobe. This was be done using the *capture* command in Adobe Premiere. It should be emphasized that this capture record was not saved and only used for editing purposes. Once the films were edited even these capture files were completely wiped off the computer to protect the identity of the participants. After the films were captured, they needed to be edited. Any pre-alarm footage was cut from all

² Short for **compressor/de-compressor**

films, so that every film started at the exact same moment, and time 00:00 minutes was when the alarm was activated. To do this, an A/B Editing Workspace was sufficient. When Adobe Premiere is launched it provides a virtual workspace where all the necessary windows for movie editing are organized. An A/B Workspace is the simplest style workspace and was sufficient for this type of project because only basic edits and changes were being made. In this workspace there is a Single View Monitor, a Timeline, and a Video 1 A/B track. A Timeline is the most important view in Adobe Premiere. It provides a frame-by-frame timeline of the film and audio tracks. It is the place where all edits can be made; so, this is a vital window in Adobe. A Single View Monitor displays a view of the frame at the location of the edit line in the Timeline. This window can also be used to view the film. The location of this edit line is the frame of the film being viewed in the View Monitor, and the edit line denotes the location where edits are being made. Finally, the Video 1 A/B track is a view on the timeline of the different components of the film or films.

Next, in order to save the film to CD each film needed to be exported out of Adobe Premiere and into a standard video file format. QuickTime was the file format that was chosen for this project, but there are other standard formats that Adobe Premiere is capable of exporting into. These files were directly exported and saved to a CD, which means that there were no other files on the PC pertaining to this drill and that the privacy of all involved was protected.

4.4 Occupant Identification

For the purpose of this report *tracking* refers to the moment in time that each individual passed by every camera during the evacuation. These tracking times were used to characterize the conditions and movement abilities of each occupant in the stairwells at different floors and at different points in time. With 269 evacuees this meant that each person needed to be distinguished from one and other, and kept track of. Keeping track of the occupants required a description for every evacuee, and this description needed to facilitate distinguishing him or her in multiple films, and in a crowd. Thus, the descriptions were in detail, and made note of any unique features (bright pink dress, very tall stature, etc). These characteristics were ones that remain static throughout the evacuation.

Each description consisted of permanent and nonpermanent characteristics, gender, and whether they were carrying an item with them during the evacuation. Some of these characteristics were used strictly for identification purposes. Others, such as gender and holding items were used for both descriptive purposes and for later behavioral studies. Also recorded with the descriptions was observational data, and door usage at the base of the stairwells. It should be emphasized that a large amount of cross-referencing between films was done to ensure accuracy and proper identification. This is because in order to protect the privacy of the individuals, a certain level of film quality was lost, so in order to verify an individual on multiple floors the most accurate way was often to open up all the films and cross-reference them.

When considering an occupant's description it was important that the descriptions could have been seen from different camera angles. The F1-double door (F1-DD) cameras faced the doorway as occupants exited the stairwells, thus occupants were seen

from the front. However, the cameras inside the stairwells viewed the occupants from the back. The identification and descriptions of the occupants were detailed enough that the occupants can be recognized definitively at both of these angles (see Figure 4.1).



Figure 4. 1 Occupant descriptions were detailed enough to recognize occupants at both camera angles

Another concern was that it was possible to have multiple occupants with similar descriptions (see Figure 4.2). These were instances when it was necessary to cross-reference films, and verify occupant identities for increased accuracy.



Figure 4. 2 Example: two occupants with similar descriptions

Permanent physical traits are inherent to an individual; therefore they are characteristics for which the likelihood of being altered during the course of an evacuation is impossible. This includes traits such as gender, race, baldness, hair color,

height, body type, and other such traits. The next portion of the description was items that were *nonpermanent* physical traits. These are physical traits that are not inherent, and are generally removable from the body. This includes clothing, footwear, dressed in a coat or sweater, hairstyle, and so forth. These non-permanent physical traits needed to be considered carefully and reexamined at every film because it was possible for occupants to remove or change the appearance of such items. For instance it was possible for an occupant to not be wearing eyewear most of the evacuation. Then, as they exited at F1-DD to prepare to go outside they put on sunglasses. Since not every floor was filmed, and some portions of the filmed floors were out of range of the cameras it was certainly possible for occupants to adjust the appearance of non-permanent traits as they evacuated. For this reason, non-permanent physical characteristics required the films to be cross-referenced quite often. However, these characteristics were noted in detail because it was possible that a non-permanent physical trait was the most distinguishing feature about a person. Wearing a bright pink scarf, or large stripes, for instance, could truly set an individual apart, but these traits were considered and watched with caution. A detailed description using both permanent and nonpermanent traits for every individual in this evacuation increased the accuracy of the tracking process and made finding individuals in multiple films more efficient. An example of permanent and non-permanent traits is provided in Figure 4.3. For the occupant featured, permanent physical traits include woman, slender frame, and mid-length hair. Non-permanent traits include black and white striped skirt, and black sweater.



Figure 4. 3 Example: non-permanent characteristics and permanent characteristics

The next portion of the each occupant's description was characteristics that both aided in tracking people through the films, and were also used later in the analysis for behavioral comparisons and studies. This includes holding items while evacuating, and double door usage at the exit of the stairwells on the first floor (F1-DD). Gender was also used in additional studies to compare parameters such as speed differences between men and women. Also a comparison of holding frequency by gender was conducted to understand which types of individuals in this evacuation tended to gather belongings before they participated in emergency proceedings, and if there is a difference in the items each gender tended to gather. This information was used to characterize the makeup of each stairwell.

Individuals that brought items with them while evacuating were recorded. Also noted was the object they were holding. The objects individuals were holding were organized into 11 categories, including backpack; coat; coffee or beverage; notebook, or papers, or books; small unidentifiable object; purse or briefcase; shoulder bag; talking on cell phone; multiple items; no items; and firefighter equipment. This encompasses a variety of size and type objects, as well as categories of objects that encourage the same

types of holding behaviors and body positions. Some of these object categories may appear to overlap each other in type, however the reasons for these distinctions will become more apparent, and explained thoroughly in Chapter 5. This data was used to consider what objects were most commonly carried during this evacuation, or whether carrying an object at all was common. Conventional hydraulic theory assumes that, upon hearing the alarm, all occupants will immediately begin to evacuate [3]. If occupants were shown to first have collected items before they proceeded to evacuate this could challenge that assumption in this particular evacuation [2]. Proulx has challenged this assumption also in her work on pre-movement time (see Chapter 2).



Figure 4. 4 Each individual that carried an object was tracked, and the object they were carrying

The side of the body the object or objects were held on was next recorded for every applicable occupant. Holding an object was considered a non-permanent physical trait because it was something that aided in describing an individual, but it had the potential to change throughout the evacuation. It was possible for the occupant to shift which side of the body they held the object on throughout the evacuation. So, the location of interest for this study was the side of the body (i.e. left or right, front or back) the object was held on the instant the individual exited the stairwell at F1-DD. Also

important was the side of the double door they used. Doorway usage is an important component of the egress process. It has the potential to be a weak link in the stairwell since everyone needs to be funneled through a channel. Typical doorway design assumes that one opens a door using the side of the body closest to the door. However, this report theorizes that if the arm closest to the door is occupied holding an object then the entire body needs to be twisted so that free hand on the other side of the body can be used (see figure 4.5).



Figure 4. 5 Using different hands to open the door created different body positions

The motion of twisting the body sideways to open the door is more time consuming and has the potential to complicate the process of exiting the stairwell. For this reason it was of interest to note, for occupants who brought objects with them, which side of the body they used to open the double door at the first floor, and which side of the double door they used.

The side of the double door used by each individual was also needed to understand flow rate at the double doors. Recall that flow rate is the amount of people that pass a fixed point per unit of time. If both sides of the double doors were used in the evacuation then this would have increased the possible flow rate when compared to only using a single door. However, the question remains whether occupants really used both

sides of double doors simultaneously. It is possible that occupants followed the person in front of them. This would have resulted in only one side of the double doors being used at a time, essentially rendering the double door a single door. Using only one side of the double door at a time could decrease the potential flow rate of double doors, but be an energy conservation process for the exiting individuals. When the flow of people is great enough, if one person opened the door then the people that follow him or her would not have to exert as much energy. This is because the door would already be partially open when they reach it (see Figure 4.6).



Figure 4. 6 Occupants using only one side of the double door at a time

Behavior that was considered non-adaptive was the next descriptor recorded. Non-adaptive behaviors generally are behaviors that hinder one self or others from evacuating. An example of a non-adaptive behavior would be untrained occupants traveling back up, or stopping in the stairwell after the evacuation has begun. This action could cause blockages and slow down others trying to evacuate. It also could hinder that particular individual from reaching safety as efficiently. The observations were categorized based upon person, floor, and time they occurred. Also behaviors that were adaptive, but still noteworthy were recorded. These are behaviors such as traveling in social groups. Traveling in a social group may not be considered to hinder evacuation,

but it is important to note how people tended to travel. To view the spreadsheets with the information described in this section see the Appendix.



Figure 4. 7 Example: traveling away from the direction of safety is a nonadaptive behavior

4.5 Firefighter Counterflow

Firefighters traveled up the Wing B stairwell in this experiment to create counterflow for the evacuating occupants. During their ascent of the stairwells, by tracking the second that each firefighter passed each camera, an analysis of the conditions that were created by two-directional movement was conducted. The firefighters traveled up the stairwells in two groups of three. The first firefighter in the first group began his ascent 80 s after alarm initiation. The first firefighter in the second group entered the stairwell 149 s after alarm initiation. To characterize the conditions of the stairwell from the firefighter's perspective, each firefighter was tracked through their ascent in a similar way as the occupants were tracked through their descent. With this information a series of comparisons were conducted:

1. Comparisons between firefighter groups. Both groups potentially encountered different conditions and densities of occupants within the stairwell because they entered at different times in the evacuation.

2. Comparisons between firefighters within each group. Each firefighter may have different personal abilities and roles within the group that could have affected their ability to ascend the stairwell.
3. Comparison between occupants in the wings with and without firefighter counterflow. Whether counterflow challenged an occupant's ability to travel down the stairwell was investigated by comparisons between the two wings.

4.6 Firefighter Identification

As with the occupants, all six firefighters were assigned personal descriptions. This description was used for the purpose of finding each individual on multiple films, and at multiple camera angles. Both permanent and non-permanent characteristics were considered for the firefighters. Permanent characteristics such as gender, race, height, and body type were recorded. Non-permanent characteristics such as uniform details and helmet color were considered. Also recorded were such non-permanent features as ranking information. Since all the firefighters were from the same jurisdiction, and were wearing similar uniforms, permanent characteristics such as race often became the most distinguishing characteristic. As with the occupants, there were often subtle differences between individuals so a large amount of cross-referencing between films was vital to an accurate analysis.



Figure 4. 8 Ranking information such as helmet color served as a descriptor for firefighters

The equipment that firefighters were holding served as an identification tool, and also was used for other analysis purposes. These are nonpermanent characteristics, but since each firefighter, and each group of firefighters had a specific role it was possible to identify a firefighter based on what he was holding.



Figure 4. 9 The different items firefighters were holding was described

The side of the double door on F1 the firefighters used to enter the stairwell was noted next. For occupants without counterflow, understanding which side of the double door they chose to use served to better understand how this doorway device was utilized in one-directional flow. For two-directional flow, it was of interest to understand if this double door device aided in facilitating organized movement of firefighters in the

direction opposing the majority of flow. Any non-adaptive behaviors performed by the firefighters were also recorded as well as the reaction of occupants to the presence of firefighters. The information concerning firefighters described in this section is included in the Appendix.

4.7 Occupant Tracking

Each occupant was tracked in this study as they passed the camera at each floor. Therefore, for every occupant that traveled in the stairwells, a timeline from beginning to end of the evacuation describes their descent. The three main goals for tracking in order of their analysis are as follows:

1. Identify each individual as they exited the stairwell.
2. Identify times that each person passed by the cameras.
3. Identify each person's floor of entry.

Tracking began with the F1 exit videos and progressively moved up the stairwell. Analysis was conducted in reverse order of how the occupants traveled because as the floor level gets higher people who entered from below floors were eliminated making analysis easier in this direction. The double door exits at F1 were the only stairwell exits in both wings. Therefore, because all occupants used these doors, this was an effective place to begin tracking and account for everyone who participated. As occupants exited, a description (using the techniques previously described) was created for each person. Then occupants were assigned a number in terms of their exit order, this is referred to as a *person number*. This number became their identity in this study, and was how they were referred to when tracked on above floors. After this step was completed, the videos

were analyzed sequentially up the stairwell. As occupants passed by each camera their time was recorded, this created a timeline for each evacuating occupant throughout different points in their descent. The floor they entered on was also noted, or if they entered on a floor not filmed.

It was important at this step to define exactly what constituted as *passing a camera*. There were two camera views in the stairwells, one looking at the landings and one looking at the double door exits on F1. Because there were two camera views in the stairwells, there needed to be two conventions for tracking. At the F1-DD, the convention for timed tracking was the second when the middle of the occupant's body crossed the doorway. If a majority of the body had not crossed through the threshold of the doorway then that individual had not yet gone through the double door (see Figure 4.10). This became an important distinction when, for example, the double doors had *queuing*. Queuing is “any form of pedestrian waiting that requires relatively stationary position for some period of time” [5].



Figure 4. 10 Tracking convention for double doors: when middle of body crossed doorway

The cameras on the landings had different views and were capturing a different behavior than those at the double doors; therefore a second convention for tracking needed to be defined. The convention for tracking at all landing cameras was the second

when each person's leading foot left the landing (i.e. the foot was raised, but had not yet landed on the step below). Once this foot left the landing the occupant was considered to be on the next floor (see Figure 4.11). As with F1-DD this was an important distinction in the case of queuing.



Figure 4. 11 Tracking convention for landings: when leading foot left landing

The information that has been determined up to this point was recorded in a Microsoft Excel spreadsheet. A sample spreadsheet is provided in Table 4.1 that describes the first four occupants in Wing A. After following the procedures in this section and previous sections in this chapter, person numbers, occupant descriptions and tracking times have been found. Also, recall that behavioral information was included in the occupant descriptions. This behavioral information included a description of all items each occupant was holding, including the side of the body the object or objects were held on as the occupant exited at F1-DD. Also, which side of the double door they used at F1 was recorded, along with any other behavioral distinctions that either aided in describing the occupant or were pertinent to future behavioral analyses.

Table 4. 1 Sample Spreadsheet: first four occupants in Wing A

# P	Gender	Description of person	Items Held	Side of body Item held on	Door used	NOTES-behaviors	F1 double doors		F2		F3		F5	
							min	s	min	s	min	s	min	s
1	M	African American, black polo short-sleeved shirt	Paper	L	L		1	7						
2	W	African American, long beaded shirt tan in color, black pants	Purse	L	L		1	13						
3	W	African American, white long button down shirt, black pants,			L		1	16	1	6	0	56		
4	W	Brown hair in low ponytail, white pants, black button down shirt	Small purse	R	L		1	18	1	5				

4.8 Firefighter Tracking

Firefighters were tracked in a similar fashion as the occupants. The firefighters were identified at the F1-DD with the occupants. As they entered the stairwell they were given a description based upon the criteria mentioned in the *Firefighter Identification* section of this Chapter. They were assigned a person number relative to the order that they entered the stairs. Their orders were consecutive and mixed in with the occupants. If, for example, five occupants exited before the first firefighter entered, then that firefighter was person number 6. By mixing the person numbers of the firefighters with the occupant it showed which occupants were affected by the firefighters as they exited, and vice versa. A firefighter was considered to have entered the F1 double doors when the middle of their body passed the threshold of the doorway (see Figure 4.12). Once the firefighters and occupants had all been identified and tracked at the F1-DD, then analysis continued by progressively tracking them up the stairwell.

As with the F1-DD films, firefighters were tracked with the occupants inside the stairwell for consistency purposes. Recall that an occupant was considered to have traveled a floor when their leading foot left the landing. To be consistent, a firefighter was considered to have entered a floor when their leading foot entered the landing (see Figure 4.12). Using these methods firefighters were tracked through their ascent and compared with each other. Also, the effect of different levels of crowdedness on their movement was determined, and the differences between the wing with and without firefighters were investigated. Figure 4.12 illustrates the firefighter tracking conventions.



Figure 4. 12 Firefighter entered when the center of the body crossed doorway. Firefighter had left a floor when leading foot entered the landing

4.9 Speed

Speed is defined as the amount of distance a moving person can travel in a unit of time. Speed was characterized in detail for each evacuating occupant and ascending firefighter in this study using the tracking times found in the previous section, and the travel path determined in Chapter 3. By calculating speed based on observational data, the objective was to obtain realistic occupant capabilities for this particular evacuation.

In the spreadsheet with the tracking records, occupants were in order of how they exited at the first floor double doors. With speed calculations however it was important

to have the occupants who traveled similar distances together, since speed is a function of both time and distance. Therefore the individuals were re-grouped based upon the floor they were first seen on. Their first recorded time (or highest floor level with a recorded time) in the spreadsheet corresponded to the floor that they are first seen on³.

Thus the occupants were in order of the floor that they were first seen on, and their *person numbers* served as a record of how they exited at the bottom. Since everyone who was first seen at a specific floor traveled the same average distance down the stairwells, the data was ready for the calculation of speeds.

There were two types of distances that needed to be determined:

1. The distance from each tracking location (i.e. each camera) to the exit of the stairwells at the F1-DDs. This is called *overall distance*.
2. The distance between tracking locations. This is called *camera-to-camera travel distance*.

The *overall travel distance* was used to determine an *overall speed* for each occupant. The *overall speed* describes the average speed an occupant traveled throughout the entire evacuation, from their first appearance to their exit. The *camera-to-camera distance* was used to determine speeds between every tracking location. This *camera-to-camera distance* resulted in a series of speeds for each occupant that describes how each person traveled throughout the different floors. This is called *camera-to-camera speed*.

In order to determine both types of travel distances the first step was to consider the path and distance traveled on each *travel component*. Any path taken inside the stairwells was expressed as a function of how many landings, mid-landings, and fights of

³ This was the floor first *seen*, and not the floor of *entry* because not every occupant was on a filmed floor as they enter the stairwell.

stairs were traveled on. Furthermore, the addition of the total amount of these components traveled on provided a complete travel path (see Figure 4.13).

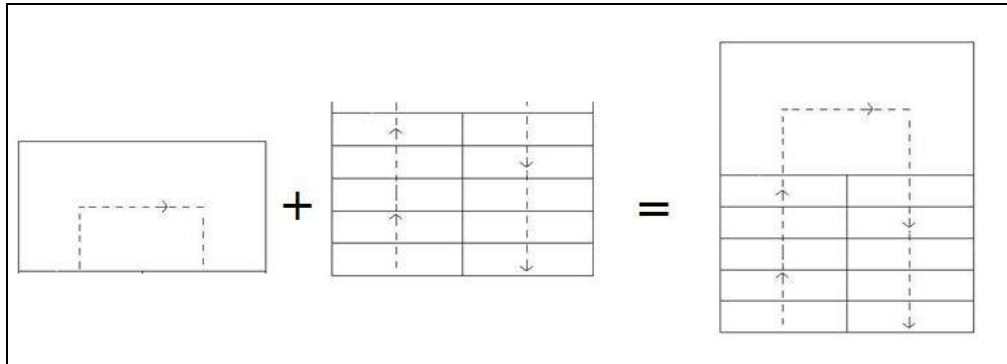


Figure 4. 13 By adding the component travel distances traveled on, travel distance was determined

Table 4.2 provides the different travel distances for each component, in each wing. This is referred to as *component travel distance*. In Chapter 3 of this report the *travel path* for each wing was defined, including the dimensions for the paths and the methodology for determining the paths. There is a distinction in Table 4.2 between *landings* and *F1 landings* because there was a different travel path on F1 landing in order to reach the exit then there was on any other landing (see Chapter 3). Also, recall from Chapter 3 that the flights of stairs between F2 and F1 in Wing B had a different number of stairs than the other flights. This was accounted for in the applicable calculations. With the *component travel distances* known, it was possible to find both *overall travel distances*, and *camera-to-camera travel distances* by adding up travel distances for all applicable components. Recall from Chapter 3 that stair components were reported in diagonal distances.

Table 4. 2 Travel distances per component

Wing B Travel Component Distances:		
Landing (m)	F1 Landing (m)	
3.56	3.40	
Mid- Landing (F5.5-1.5) (m)		
3.56		
Flight of Stairs (m)	Flight of Stairs (F2 to1.5) (m)	Flight of Stairs (F1.5 to1) (m)
3.13	2.44	3.83

WING A Travel Component Distances:	
Landing (m)	F1 Landing (m)
3.56	4.65
Mid- Landing (m)	
3.56	
Flight of Stairs (m)	
3.13	

At this point, all necessary travel paths were found by the addition of all the component distances in each path. An example the travel path calculation is provided in Example 4.1.

EXAMPLE 4.1: To determine the travel from F3 to the double door exit at F1, in Wing A the following expression is used:

(4)(stair flight) + (2)(mid-landing) + (1)(landing) + (1)(F1 landing) = Distance from F3 to F1 exit.

$$(4 \times 3.13) + (3.56) + (2 \times 3.56) + 4.64 = 27.84m$$

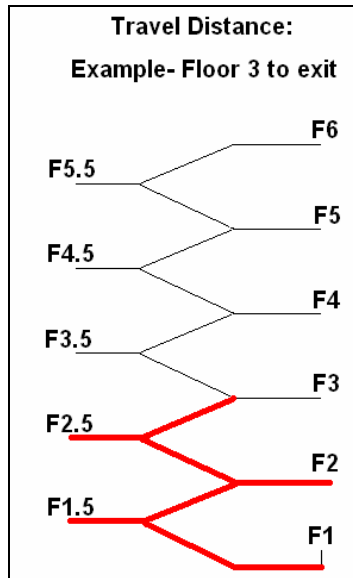


Figure 4. 14 Travel distance from F3 to F1 exit

The camera-to-camera distances, and the overall distances were calculated using the method illustrated in example 4.1 and are provided in Tables 4.3 and 4.4.

Table 4. 3 Overall and camera-to-camera travel distances for Wing A

Overall Travel Distance:		Camera-to-Camera Travel Distance:	
Floor	Distance Traveled (m)	Floor (From → To)	Distance Traveled (m)
5	44.03	5 → 3	26.75
3	27.84	3 → 2	13.38
2	14.47	2 → 1	14.47

Table 4. 4 Overall and camera-to-camera travel distances for Wing B

Overall Travel Distance:		Camera-to-Camera Travel Distance	
Floor	Distance Traveled (m)	Floor (From → To)	Distance Traveled (m)
5.5	60.04	5.5 → 3.5	26.75
3.5	29.73	3.5 → 2.5	13.38
2.5	19.91	2.5 → 1.5	12.68
1.5	7.23	1.5 → 1	7.23

At this point all necessary distances had been calculated, and occupants were grouped by floor of first appearance. Overall speed was determined from the overall descent time. *Overall descent time* is the total amount of time spent in the stairwell from the moment of first appearance to the time of exit, i.e. for every occupant the time first seen was subtracted from the exit time. Their time first seen corresponds to the highest floor in which an occupant had a recorded time, and their exit time refers to their F1-DD exit time, as seen in Table 4.1. The overall travel speed of each occupant is defined as the rates of their overall travel distance to the descent time. The overall speeds determined at this point are reported in Chapter 5.

A similar approach was used to determine camera-to-camera speeds. Now instead of finding overall descent times, descent time was determined between every tracking location. Therefore the time it took each occupant to travel between floors with cameras was found. In Wing A, the times required to travel from 5 to 3, 3 to 2, and 2 to 1 were found. Similarly, in Wing B the time it took to travel between 5.5 to 3.5, 3.5 to 2.5, 2.5 to 1.5, and 1.5 to 1 was found. These times correspond directly to the camera-to-camera distances. Therefore, camera-to-camera distance divided by time at each different location for each different occupant yields the average speed each person traveled between each tracking point. This data is reported in Chapter 5.

The speeds of firefighters were determined in similar ways as the speeds of the occupants. For every firefighter overall and camera-to-camera descent times were determined. The appropriate distances were divided by the appropriate times, to yield overall and camera-to-camera speeds. Since every firefighter entered and exited on the same floor, they all traveled the same distance. This made the speed calculations more

straightforward for the firefighters than for the occupants. Furthermore, all tracking locations were at the same points in the stairwells for the firefighters and occupants, only in the reverse direction. Therefore, the distances used to find the occupant travel distances were used to determine firefighter travel distances.

4.10 Density

Density is defined as the amount of people per unit area. This portion of the analysis focused on the methods used to analyze how population density affected this evacuation. For analysis purposes, density was considered from an Eulerian Fluid Mechanics style viewpoint. This viewpoint considers changes in flow as they occur at a fixed point in the fluid flow. In this case, the evacuating population was the flow, and the particles were the people. The moving population was monitored from a fixed location in the stairwell (i.e. the cameras). Traditional hydraulic theory often treats an evacuating population as thoughtless particles, with no cognitive abilities that could cause disruptions or complications. In this case, fluid mechanics was only used to define the observational perspective. Thus, the viewpoint for observing density was the camera at F3 in both wings because the largest segment of the population was first seen at this floor. This was primarily because there was not a camera at F4, thus anyone who entered at F4 or F3 was first seen at F3. This location was also chosen because in Wing B there was a significant amount of congestion associated with the firefighters on F2.5. As a result queuing and stoppages were experienced on F3 making this a good location to compare Wing A and Wing B. Since this floor was representative of the conditions

experienced in the middle in the stairwell, and not directly next to the exit this was an acceptable location for comparison between the wings.

Once the floor of interest and the perspective of this analysis were defined, the area within that floor of interest was considered. Density is the amount of people in a defined area at any moment in time. Therefore an area of known dimensions needed to be defined on F3 (this is referred to in this report as a *density area*). Also, this space needed to include only one type of travel component. An area covering two types of components, such as a landing and a staircase, would have included individuals performing two different operations. Some would have been traveling down stairs, and some would be walking on a horizontal component. Thus, by defining the area as either a staircase or a landing, occupants within the density area were performing the same movement operation. Therefore, the upper flight of F3 staircase was defined as the density area, since it was in view in both camera angles. See Figure 4.15.



Figure 4. 15 Density area was the upper stairwell on F3 in both wings

Area was determined using the diagonal distance of the staircases times the *travel width* of the stairs. Since the handrail (side attached to the wall) took up 5 inches of the width of the stairs this amount was subtracted from the total width (this is a known,

measured value that was determined on the day of the drill). Therefore, the density areas were 4 m^2 in Wing A, and in Wing B it is 4.4 m^2 .

Every 10 s throughout the evacuation snapshots were taken of the F3 landings in both wings using Adobe Premiere Video Editing Software. These snapshots were not saved to the PC; they were simply viewed, analyzed, and then deleted. The snapshots provided an instantaneous representation of the density area at each time interval. To verify that this time interval would not over-sample the population, the length of the density area (3.12 m) divided by the slowest overall speed (0.4 m/s) needed to be less than 10 s. Since it was determined that this time is 7.8 s, then 10 s was an adequate sampling time. The, by counting the number of people in the density area at each of these snapshots and dividing this value by the density area a representation of density was determined throughout the evacuation (see Figure 4.16). As with all tracking analyses in this report, an occupant was considered to have left the density area when their leading foot left the staircase. Conversely, they were considered to have entered into the density area when their leading foot left the landing above.



Figure 4. 16 To determine density, everyone in the density area at each snap shot was counted

Density is considered by many conventional egress models to be directly linked to speed. Furthermore, some models even make the assumption that speed can be solely

controlled by density (and vice versa). To investigate this assumption, it was of interest to know how fast people who experienced different density levels within the density area were able to travel. Therefore, for every person in a density snapshot, the speed at which they traveled through the density area was of interest. The density in each density snapshot was known; therefore finding the speed that they traveled through this area provided a measure of speed capabilities given a certain density. Since overall and camera-to-camera speeds were tracked for a different area a new speed just within the density area was calculated. Therefore, for each person in each snapshot, the time they entered into the density area and the time they left the density area was recorded. The difference between these times divided by the length of the density area, provided the speed of each person as they traveled through the density area only.



Figure 4. 17 For people seen in each snapshot the speed as they traveled through the area was determined

Another parameter that is accepted by conventional egress modeling to be directly controlled by density is flow rate. Recall that flow rate is the amount people that can pass a fixed location in a unit of time. As with speed, in order to make a direct comparison

between the density values determined in each wing and flow rate, the flow rate specifically through the density area was determined. Recall from Chapter 2 that flow can be calculated as the product of speed, density, and width. The speed through the density area was determined for each occupant, in each snapshot. Using these values and the density each of these occupants experienced, the flow rate for each snapshot was determined as a function of density.

Since every firefighter traveled up F3 in Wing B they too were counted in the density area if they were in the snapshot. Even though they were traveling in the opposite direction of the occupants, at any instant they still contributed to the total population of the stairwell, and thus the density. Moreover, their effect on density was of interest in this analysis. By comparing the evolution of density in F3 in both wings, insight was gained as to how counterflow affected the level of crowdedness in this evacuation.

4.11 Flow Rate

Flow rate is often considered to be a fundamental egress parameter, and was considered from two additional perspectives in this study:

1. Flow rate out the double doors at the F1 exits, and
2. Overall flow rate throughout the stairwells.

The flow rate is a measure of the quantity of people that pass a fixed point in a unit of time. Consider the double door exits at F1, this was the fixed point, and the unit of time was defined as 5 s. Thus, the amount of people that pass through the double doors every 5 s was needed for this analysis. These totals divided by 5 s will yield a value of people

per second for every 5 s interval from beginning of the evacuation until the end. Note that these intervals did not overlap. As with other F1 double door exit analyses in this report, an occupant was considered to have traveled through the double doors when the middle of the body crossed the threshold of the doorway (see Figure 4.18).

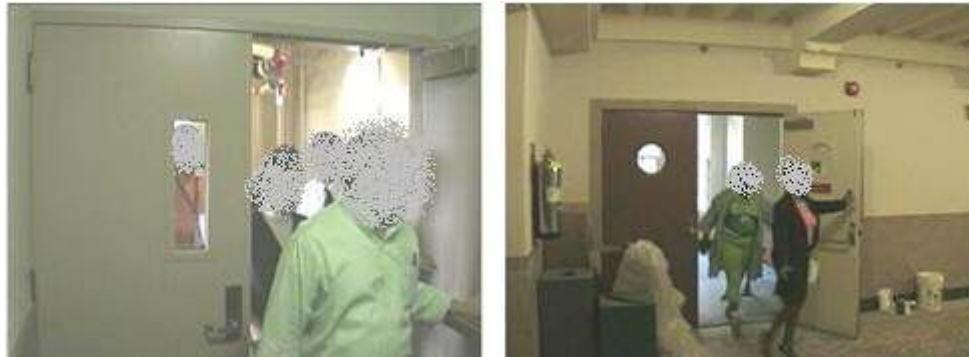


Figure 4. 18 Every 5 s the number of occupants that crossed F1 exit was tracked to obtain flow rates

Flow rate was also determined for the whole stairwell. To do this the total number of people inside both stairwells every 10 s was determined. This consisted of a series of *if-and statements* for every person at every 10 s time interval. An *if-and* statement is when one value is assigned *if* a condition is met and another *if* the condition is not met. In this case, if an occupant was somewhere inside the stairwell they had a tracking time recorded at the location they just passed. For this analysis, it did not matter where they were in the stairwell because the concern was the total number of people inside the entire stairwell at any given time. Thus, any recorded time, at any floor, meant they were somewhere in the stairwell at that time interval. Therefore the following statements were programmed in Excel:

“If person number *blank* has a time recorded at *blank* time interval, assign them a value of 1. OR

If person number *blank* does not have a time recorded at the *blank* time interval, assign them a value of 0.”

Thus a value of one means the person was somewhere inside the stairwell, and a value of zero means they were not inside the stairwell. Then for every time interval this statement was repeated for every person. This was done every 10 s from the activation of the alarm to the end. Finally, totaling up the number of 1’s assigned at a specific time interval corresponded to the amount of people inside the stairwell at that moment. This was done for both stairwells from beginning to end. Then a percent of the total population for every time interval was determined using the total population that traveled through each of the stairwells. Then results of each wing were compared. An example of this style of analysis is provided in Example 4.2.

EXAMPLE 4.2: Consider a stairwell where three people total travel down the stairwell at different points in time. An *if-and* analysis regarding the total population has been conducted at every 10 s.

- Person A enters the stairwell at 60 s and exits at 120 s.
- Person B enters the stairwell at 80 s and exits at 140 s.
- Person C enters the stairwell at 90 s and exits at 150 s.

Table 4. 5 Example if-and analysis to determine overall stairwell population

Time Interval (s)	Person A	Person B	Person C	Population	Percent of Total Population
50	0	0	0	0	0
60	1	0	0	1	33
70	1	0	0	1	33
80	1	1	0	2	67
90	1	1	1	3	100
100	1	1	1	3	100
110	1	1	1	3	100
120	0	1	1	2	67
130	0	1	1	2	67
140	0	0	1	1	33
150	0	0	0	0	0
160	0	0	0	0	0

After this analysis was completed the total percent of people inside the stairwells throughout the evacuation was known; this was graphed with respect to time. The population in the stairwell versus time is a flow rate measurement, with the results reported in Chapter 5.

Chapter 5: Results

5.1 Introduction

This chapter provides the results and analysis of the six-story office evacuation. The commonly accepted, essential egress parameters (speed, density, and flow rate) and their interactions with each other were investigated. Then, human behavior was investigated as a fourth parameter. Both qualitative and quantitative results are provided.

5.2 Speed

Camera-to-camera speed and overall speed are the primary forms of speed reported in this study. From this point forward camera-to-camera speed is referred to as *local speed* for analysis purposes. Recall from Chapter 4 that local speed is based on the tracking times for every person, and the travel distance between tracking locations. Also recall from Chapter 4 that overall speed corresponds to the average speed that each person travels from the floor they were first seen on to when they exited the stairwell at the double doors on F1.

Figure 5.1 describes the frequency of overall speeds of the occupants in each wing. In Wing A approximately 50 percent of the population traveled between 0.7 and 0.8 m/s. In Wing B, the wing with firefighter counterflow, approximately 50 percent of the population traveled at an overall speed of 0.5 to 0.6 m/s. The mean speed for Wing A was also slightly faster than Wing B, as well as the minimum and maximum overall speeds achieved (see Table 5.1). This suggests that the wing without the counterflow had slightly higher overall speed capabilities. However, based on the standard deviations for overall speeds in the two wings, this phenomenon can only be discussed as a trend.

Speeds at which only 4 percent or less of the population traveled at generally mean that those individuals were *outliers*. These occupants were usually observed at the end of the evacuation. They were often times observed to be moving faster than the general population and at the end of the evacuation, or they were moving very slow at the end and hanging on to the handrail. Some of the outliers were also security guards or floor wardens that traveled at the end of the drill as per their instructions from the building owners. There were even cases where the occupants slowed down because they were socializing in the stairwell and then when they resumed their movement they dramatically increased their speed, which subsequently increased their overall (or average) speed. There were more outliers noted in the Wing A evacuation. It is not clear what the reason for this was.

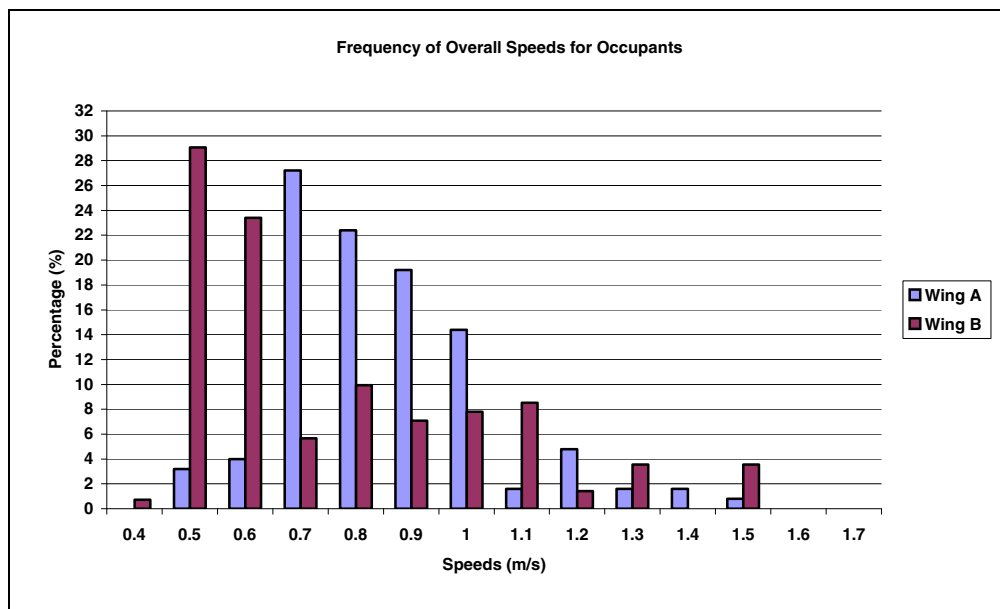


Figure 5. 1 Frequency of overall speeds for occupants in both wings

Table 5. 1 Descriptive statistics for overall speed

	Wing A	Wing B
Minimum Overall Speed (m/s)	0.46	0.23
Maximum Overall Speed (m/s)	1.47	1.40
Mean Overall Speed (m/s)	0.80	0.70
Standard Deviation (m/s)	0.19	0.26

The higher in the stairwell one entered, in theory, the greater the impact of the counterflow. This is because for higher floor levels, more people would have been affected by a stoppage from a lower floor. Thus, the difference in speeds at higher floors versus those at the lower floors in each wing was considered. It is also necessary to compare each floor in Wing B to its non-counterflow complement floor in Wing A. To do this every person's local speed was averaged together by camera location. This provided an average speed traveled at each floor location (see Figure 5.2). The graph in Figure 5.2 was broken into 4 segments; these segments are associated with the camera locations that are comparable in each wing. Recall that because of the different landing geometry in each wing the cameras were placed in slightly different locations. The location of the cameras in Wing B provided a poor view of the landing at each floor, which was the desired view. Thus, the only viable solution was to track occupants a half floor up. Therefore, landings in Wing A were compared to mid-landings in Wing B. Also recall that Wing B had one more camera in the stairwell than Wing A, at F1.5. Therefore the shaded boxes correspond to the cameras at the comparable floor locations. The "Floor" reported on the x-axis of the graph corresponds to the first tracking camera location. For example, the data point at $x=5$ is the speed determined from the camera on F5 to the next tracking location, which in this case is F3.

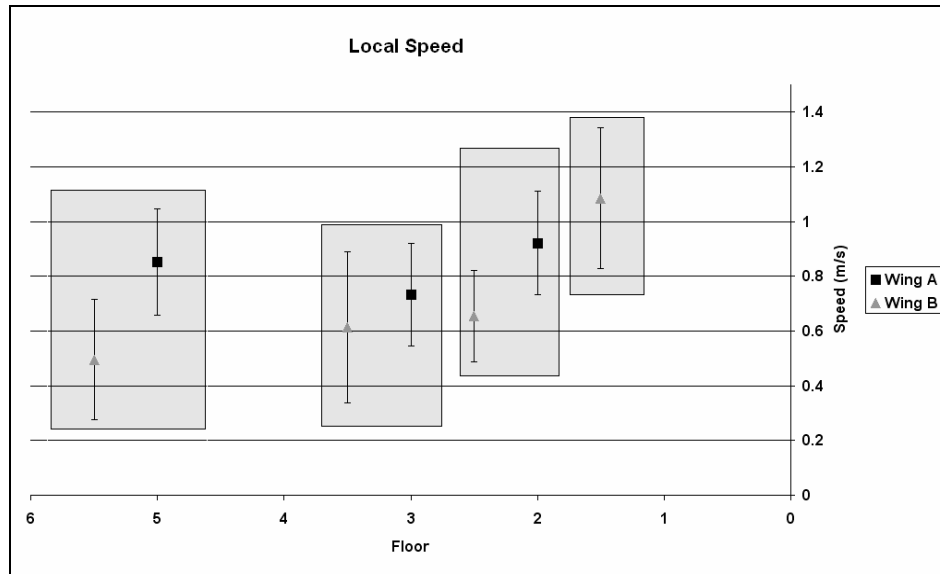


Figure 5. 2 Local speed for occupants, with standard deviations

Since all of the error bars, corresponding to the standard deviations of the data, overlap any conclusions drawn from Figure 5.2 were done so with great caution. Two general trends were observed in this data. The local speeds obtained at the cameras in Wing A all stayed around the same value of 0.8 m/s. They did not have a general increasing or decreasing pattern. Since 50 percent of the population in Wing A also had an *overall speed* between 0.7 m/s and 0.8 m/s this suggests that a relatively even pace was maintained throughout the stairwell since the overall and local speeds did not vary much from one and other. In Wing B however, the trend was for the speed to continue to increase for occupants as they descended to lower floors. This implies that counterflow became a less significant issue as one reached lower floors, and that occupants could attempt to recuperate some time at the bottom by speeding up. It would be best however, to repeat this study for a building with more floors to see if this trend continues or even grows.

The second major trend observed is that F5 and F5.5 in Wings A and B experienced the greatest difference in speeds between any two complimentary floors in the two wings. This too suggests that the higher the floor level the greater the effects of counterflow were. Again, this study could be repeated in a building with a greater number of floors to draw a more definite conclusion. F2 and F2.5 also had a large gap in speeds in the two wings. This is most likely attributed to the fact that this floor was observed to be one of the most crowded in Wing B. Another interesting trend is that the speeds at F1.5 were appreciably greater as compared to the other floors in Wing B. Again, this suggests that the effects of counterflow increased with increasing floor level.

Next, the local speeds were used to create a timeline for each person that exited at the base of the stairwell (see Figures 5.3 and 5.4). As with Figure 5.2, in Figures 5.3 and 5.4 the x-axis or “Floor” corresponds to the first camera location. Therefore $x=5$ is from F5 to F3, and so on. For these figures, only occupants who were first seen at F5 were included. The reason for this is that the next camera location was at F3 or F3.5, and these individuals only have two data points, which is not enough information to present.

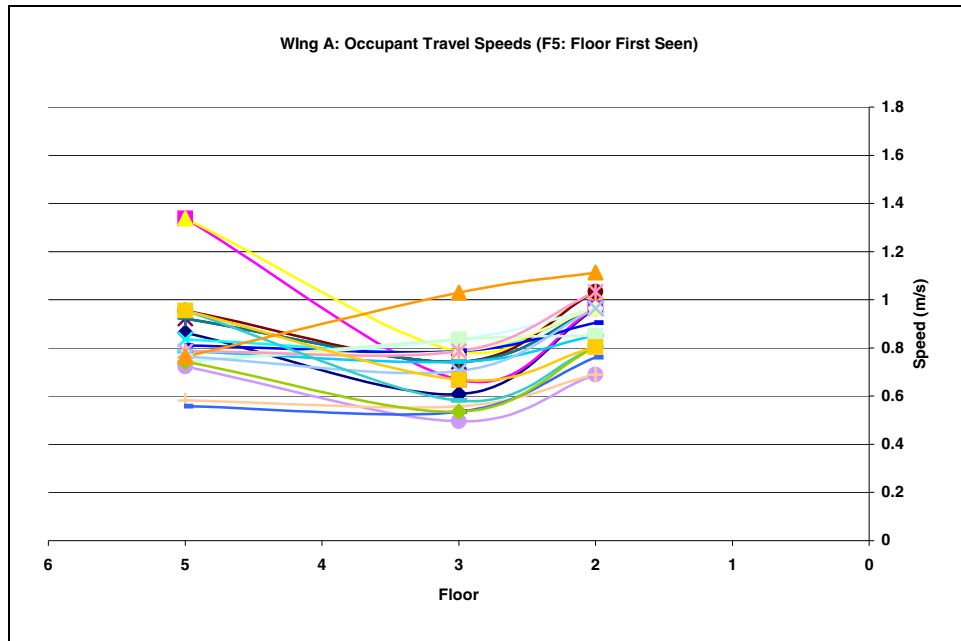


Figure 5. 3 Wing A: Occupant local speeds for individuals first seen on F5

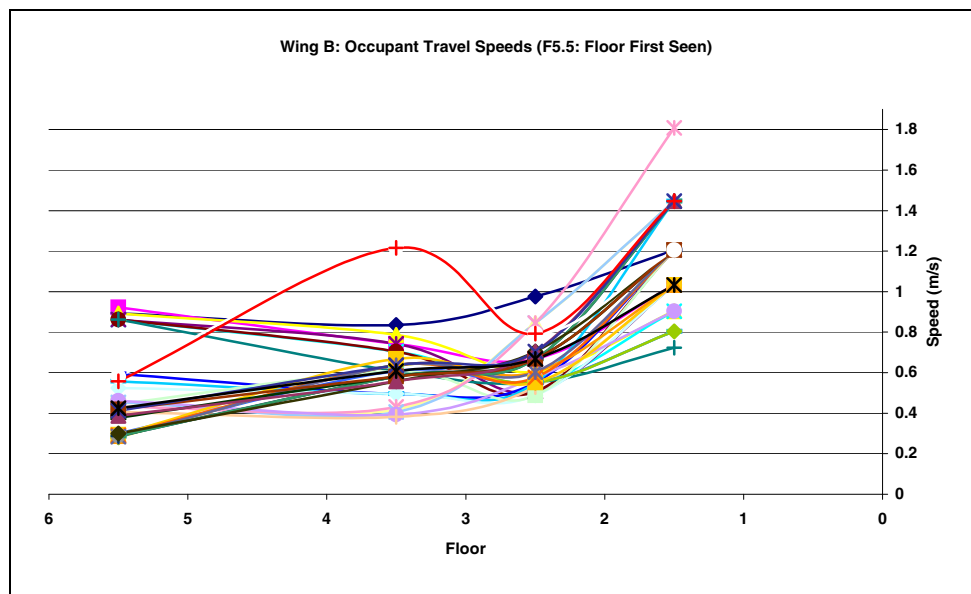


Figure 5. 4 Wing B: Occupant local speeds for individuals first seen on F5.5

Each curve in Figures 5.3 and 5.4 represents an individual person. The bulk of the population in Wing B, in general, traveled slower than the population in Wing A. However, the highest and the lowest speeds were achieved in Wing B, and there was

more fluctuation in the speeds traveled between different floors in Wing B. Also, in Wing B there was a tendency for occupants to speed up at the bottom of the stairs, and move slower at the top. This is the same trend discovered in Figure 5.2 where local speeds at the different floors were averaged together. This is attributed to counterflow not affecting the population as significantly at the bottom of the stairs, allowing occupants to speed up right before they exit. There was no case of anyone who entered at F5.5 in Wing B moving faster at the top of the stairs than at the bottom. But, in Wing A, there were a few individuals that did this, which shows that occupants in Wing B did not have the option to go faster at the top. The occupants in Wing A maintained a similar speed at the beginning of their descent as they did at the end. Those who sped up did so very slightly (in most cases approximately 0.1 m/s). In Wing A the occupants also had a decreased local speed in the middle of the stairwell, which is attributed to increased levels of crowdedness and occupants that performed such nonadaptive behaviors as traveling back into the building, creating minor amounts of isolated counterflow.

Also note in Figure 5.4 that between F3.5 and F2.5 in Wing B, a dip in many individual's local speeds can be seen, before their speed picked up at the bottom of the stairs. This is a logical finding since F2.5 was the most congested floor that firefighters had to travel through in this wing. The counterflow conditions, coupled with the extra crowdedness at this floor, in turn slowed the occupants down. In fact, it also slowed the firefighters down as well. In Figure 5.5 the speed of the firefighters decreased sharply as they traveled from F1.5 to F2.5. Since the point of congestion was at F2.5, all groups felt the decrease in speed at F2.5 and at the floor before they traveled through the congestion. In the case of the firefighters the floor before the congestion was F1.5, and for the

occupants it was F3.5. Note that the numbers in the legend in Figure 5.5 correspond to the firefighter group number and the order they entered (for example, FF1.3 means the firefighter is in Group 1, and was the third to enter the stairwell in his group). Also, in Figure 5.5 note that Firefighter 1.1 has the fastest local speed curve, and Firefighter 2.3 has the slowest and everyone in between is basically in the order of how they entered. This means that as the stairwell became more crowded, and the effects of counterflow greater, each firefighter's speed was intimately affected. This effect can also be seen with the overall speed of the firefighters. In Figure 5.6 the Firefighter's overall speed was graphed against their order of entry (i.e. x=1,2,3 means first, second, and third firefighter in the stairwell), and each data series represents the two different groups of firefighters. From this graph it can be seen that Group 1 always traveled at an overall faster speed than Group 2, and the earlier each firefighter entered the stairwell the faster they went.

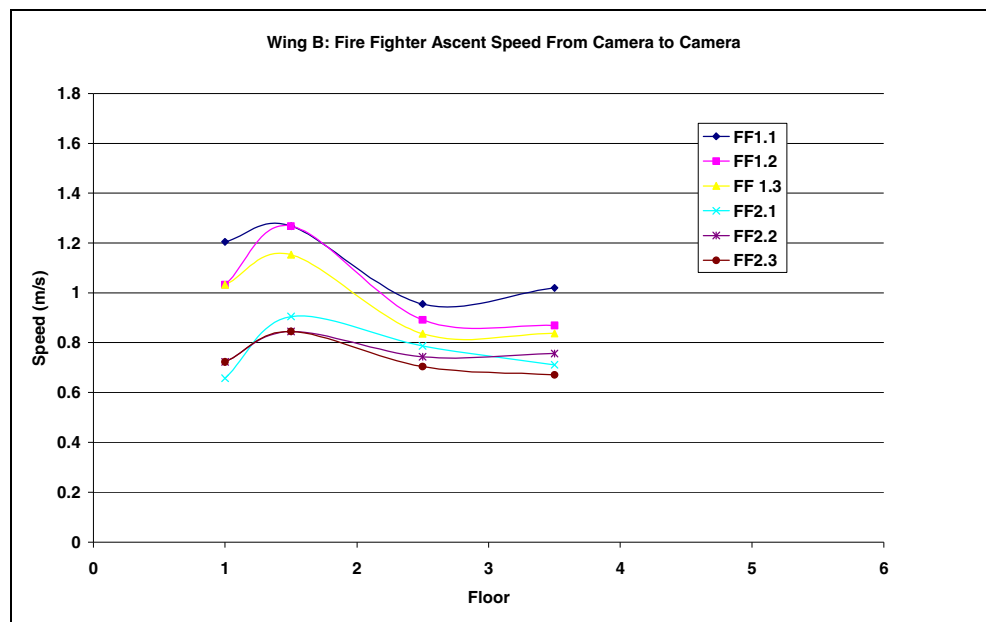


Figure 5. 5 Firefighter ascent speeds from camera to camera

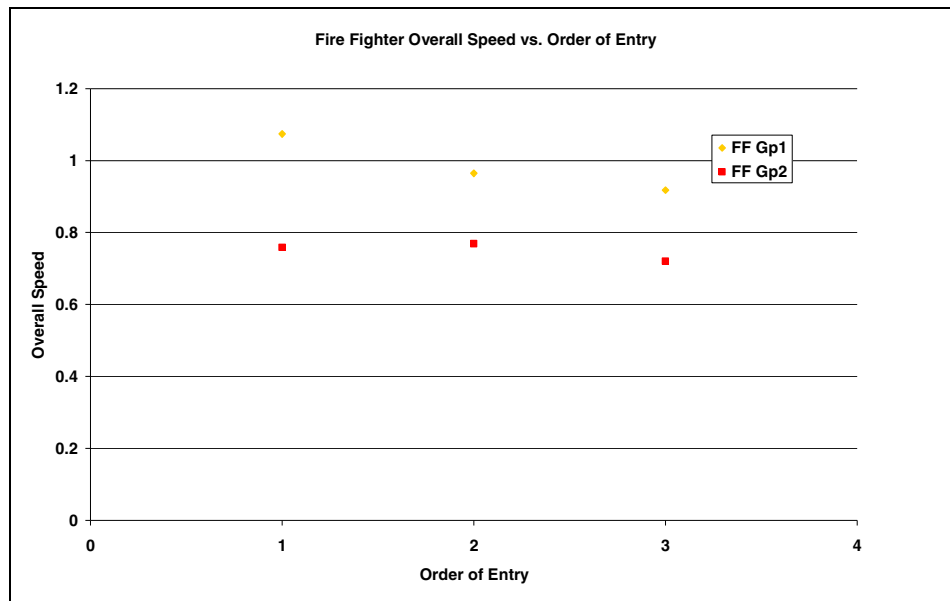


Figure 5. 6 Firefighter overall speed as a function of entry order

Another trend in Figures 5.3 and 5.4 is the fact that in Wing A (Figure 5.3) there appears to be more space between each individual's local speed curves; whereas in Wing B many of the curves are clumped together. This shows that there was more of a choice in Wing A regarding how fast or slow an individual could have traveled; whereas in Wing B people were more confined to travel at the speed of the crowd. From Figures 5.1 through 5.6 counterflow made a small but noteworthy difference in the speeds of each individual throughout the stairwell. It also caused fluctuations within the speeds traveled throughout the evacuation. In a taller building it is possible that either the effects of counterflow could be more significant because there is more room to compound the problem, or counterflow is less significant since occupants would have more distance to recover time and speed up. Also, a narrower stairwell could significantly impact the effects of counterflow. The stairwells in the current study were relatively wide. In this building it appears that counterflow made a difference on speed capabilities.

5.3 Density

The effects of density on the basic people movement parameters were studied by determining density versus flow rate and density versus speed in both wings. Since the area for the density assessment (called *density area* in this report) was the same in both wings (the staircase above the F3 landing, see Chapter 4) the issue of comparing floors to half floors was not a concern in this calculation. Also, this area was chosen because it incorporates only one staircase in the calculation (i.e. no landings, or other horizontal components, and only one stretch of stairs). This way, only one type of movement was being accounted for in the calculation (i.e. vertical stair movement), and for comparison purposes it most closely represented the calculations performed in the literature. F3 in both wings was chosen as a representative floor because it was the camera location at which the most people were *first seen* on. This is because there was no camera at F4 or F4.5, so anyone who entered at this floor was first seen at F3 or F3.5, as well as the individuals who entered at F3 in Wing A. Also recall that for the occupants of Wing B, this floor was above the area of most congestion, which was F2.5, so in theory stoppages and queuing would be greatest on the floor above.

The timeline of events is duplicated in Figure 5.7 with the graph of density versus time in the two density areas.

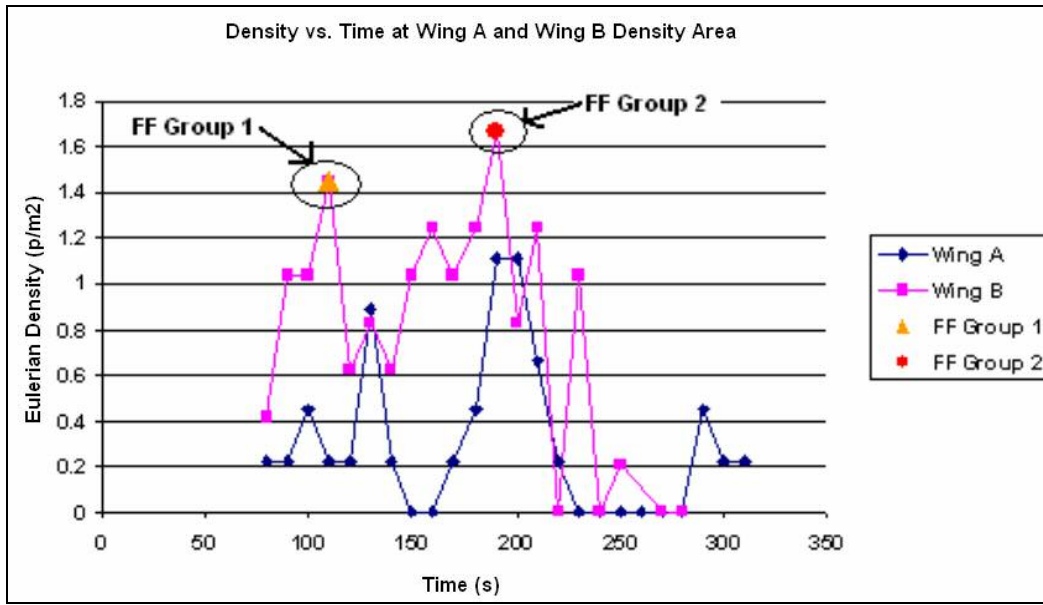


Figure 5. 7 Density versus Time in Wing A and Wing B density area

In general, Wing A experienced lower densities than Wing B for the duration of the evacuation. This is a consistent finding since Wing B was the counterflow wing; this agrees with the hypothesis of the research. It should be noted however that there was a difference in the densities in the two wings before the firefighters had an impact.

There are two notable points to discuss at 130 s and 200 s after alarm. At these points, the density in Wing A exceeded that found in Wing B, with Wing A reaching peak values and Wing B reaching low values. These two points in time occurred after the evacuation was well underway (i.e. not the very beginning or the very end of the evacuation). These points are noteworthy because both of the peaks in the Wing A dataset directly coincided with drops in the density for Wing B; the cause of which is unknown. Even more intriguing is that the drops in Wing B directly followed the moments right *after* the firefighters passed by.

Before these density drops however, there was an increase in density the moment the firefighters passed by (Figure 5.7). This demonstrates that the presence of firefighters

increased the density. Then, right after the firefighters passed there was no longer counterflow at that location because the firefighters had moved to the next floor above. This caused two things to happen, first when the firefighters left the original floor those occupants resumed their motion, second when the firefighters moved to the next floor above these newly exposed individuals stopped or slowed their motion. Thus, there was movement out of the floor but slowed movement into the floor. This created a momentary decrease in the density directly following the presence of the counterflow. However, after motion was resumed, even though the density dropped sharply, Figure 5.7 shows that the occupants in Wing B never fully recovered the density to the level it was at in Wing A. The dips in density experienced right after the firefighters passed by only enabled the Wing B density area to essentially reach the peak values of the non-counterflow Wing A. It is also important to note that after the second group of firefighters past the density area, the density did not recover to the same degree it did the first time the firefighters passed by.

Figures 5.8 and 5.9 offer further investigation into the relationship between the density and velocity. Recall from Chapter 4 that the velocity within the density area was calculated for each person in each density group (see Chapter 4). Thus, the velocities considered at this point are strictly the velocities of the individuals who were experiencing the corresponding densities. Proulx's correlation presented in its general form as Equation 2.2 in this report, was used at this point for a 7 by 11 inch stairwell, and was superimposed on the graphs with the results from the current study. This was done to give a sense of what a standard and widely used model for determining speed, based upon density, would yield as compared to the data found in this study. Other correlations

provided in the literature review (Chapter 2) are considered in the next chapter (Chapter 6). The R^2 values and trend lines for the data are also reported on the graphs. It should be noted that low R^2 values are expected when human behavior is a factor because in this case for example, there are lots of other factors that could be affecting velocity other than just density.

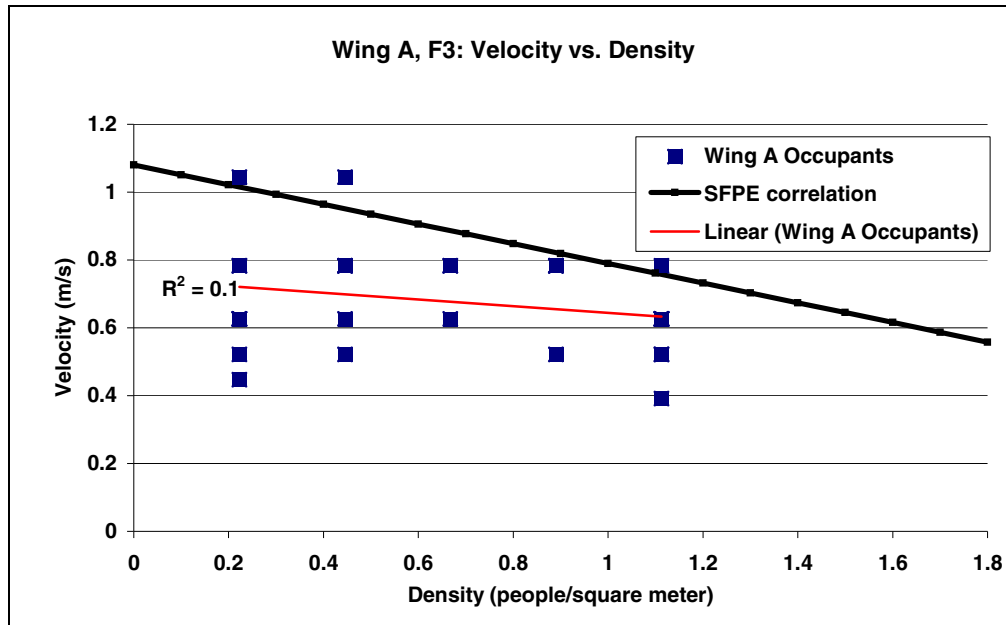


Figure 5.8 Wing A, F3: Velocity versus Density, with SFPE correlation

The range of densities experienced in Wing A was from 0.2 to 1.1 people/m² (see Figure 5.8). In Wing B the range of densities was from 0.2 to 1.7 people/m², but the majority of the occupants experienced a density of between 0.6 and 1.7 people/m² (see Figure 5.9). Thus the wing with counterflow had a higher range of densities than the wing without counterflow. Also not surprising is that Wing B experienced slower speeds inside the density area than Wing A. For the Wing A results the R^2 value was 0.1, and for the Wing B results the R^2 value was 0.2.

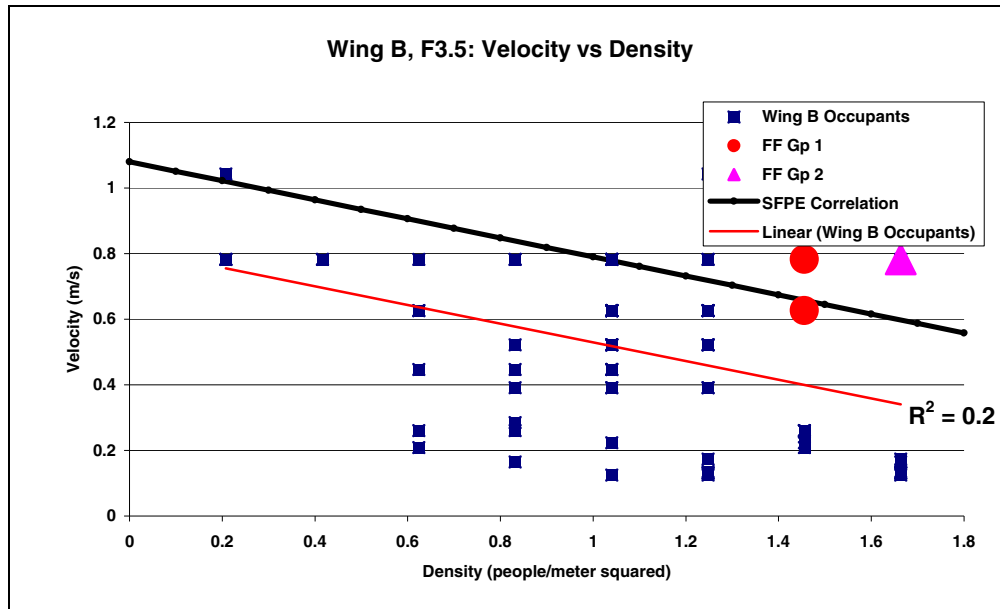


Figure 5. 9 Wing B, F3: Velocity versus Density, with SFPE correlations

In Figure 5.9, for Wing B, the range of achievable speeds was much lower than that in Wing A, and the density range was much higher. This reaffirms the hypothesis that the range of speeds would be lower in the wing with counterflow, and that density would be higher. Furthermore, both wings traveled at speeds that were generally lower than the correlation in the SFPE Handbook predicted, for the entire evacuation and at all the different density levels. It is also important to emphasize that the correlation in the SFPE Handbook generally over-predicted speed at the different densities in both wings, regardless of counterflow conditions. The SFPE correlation provides an upper-limit prediction for this evacuation. Also in Wing B, the data points where the firefighters were present produced the greatest densities in the duration of the evacuation at this floor.

5.4 Flow Rate

The flow rate was determined for the same density area in each wing. This was done using the following equation:

$$F = S \times D \times W_{eff} \quad \text{Equation 5.1}$$

Where:

F= Flow rate (people/s)

S= Population speed (m/s)

D= Density (people/m²)

W_{eff}= effective width of the stairwell

[3]

Equation 5.1 is found in Proulx's chapter of the SFPE Handbook [3]. The experimental data for flow rate is provided at the range of densities observed, as well as the results of the model provided in Equation 5.1. As with speed previously reported in Figures 5.8 and 5.9, this provides an idea of how the experimental data compares to a commonly used model (other models are discussed in Chapter 6). This means that first the speeds observed in the density area were used as an input into Equation 5.1. Then the model for speed provided by Equation 2.2 was used as the speed input in Equation 5.1. The R² values and the trend lines for the data in this study are provided on the graphs in this analysis as well. Similar to the speed versus density analysis, R² values were expected to be low because human behavior was a factor.

In Figure 5.10, for Wing A, as the density increased so did the flow rate, this created an increasing trend in the curve. In Wing B, a similar trend was noticed (Figure 5.11), until a density of approximately 1.3 people/m² where occupants could no longer maintain the increasing pattern. Also interesting is that the flow rates in Wing A,

remained within a small range at each density level. Whereas Wing B had a large range of flow rates at each density level, even though the curve still follows a general increasing trend. As with the velocity curves, this SFPE correlation generally over-predicted the flow capabilities of this population, especially the population of Wing A. However, what is interesting is that this correlation better predicted the flow rate *with* counterflow conditions than without. For the Wing A results the R^2 value was 0.9, and for the Wing B results the R^2 value was 0.3. A polynomial curve fit was used at this point even though a linear curve fit was used previously for the speed data. This is because these were the most accurate fits for each set of data. A linear curve fit did not capture the nature of the flow rate data as well as a polynomial. The polynomial curve fit used is second order.

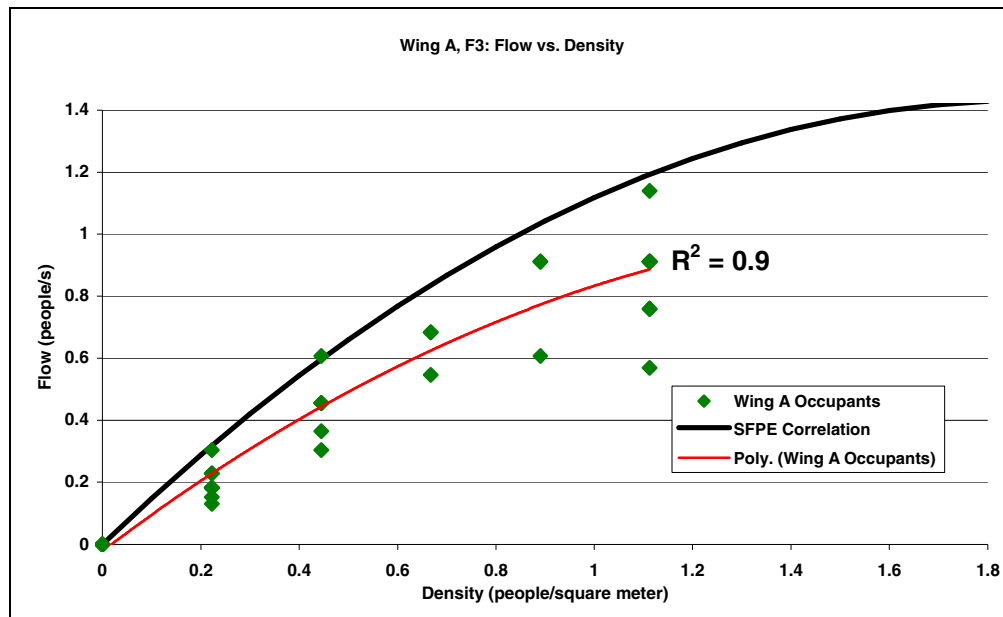


Figure 5.10 Wing A, F3: Flow versus Density with SFPE correlation

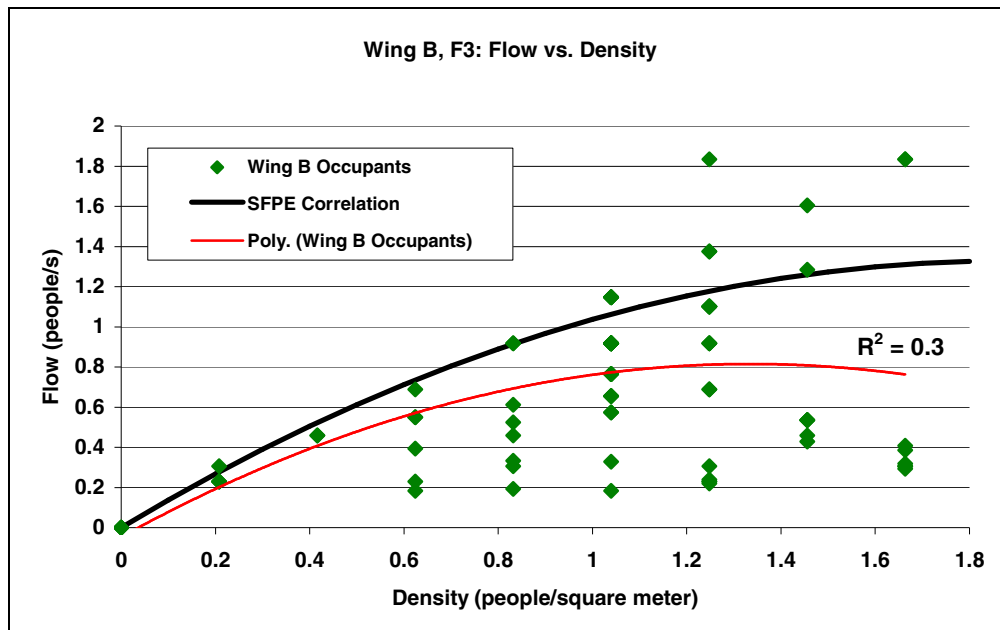


Figure 5. 11 Wing B, F3: Flow versus Density with SFPE correlation

Queuing and stoppages were hypothesized to have the potential to slow occupants and firefighters in an evacuation. Also hypothesized was that if counterflow were inhibiting movement, as people stopped in the stairwell to let the firefighters pass, an ever growing population would accumulate in the stairwell. Quite often during the evacuation, occupants were observed to literally stop in place, or move to the side and stop, to allow the firefighters to pass even when the conditions in the stairwell did not require them to stop. Queuing was the greatest in Wing B at F3 but was not exclusive to this floor, and occupant stopping to allow the firefighters to pass was observed on all floors the firefighters traveled in.

To investigate this hypothesis the number of people in each stairwell overall was determined at 10 s intervals. Each of the wings had similar conditions prior to entering the stairwell, all stairwells were evenly positioned throughout the building, and a comparable number of total occupants traveled through both wings. Thus, answering two

questions tested the proposed theory. First, prior to the firefighters entering the stairwell, did the number of people in each of the stairwells increase at a similar rate? Second, after the firefighters entered, were there more people in Wing B at any moment, when compared to the same moment in Wing A?

At 10 s intervals, and using the occupant and firefighter tracking times (see Chapter 4), the moment in time each individual was somewhere in the stairwell was determined (method described in Chapter 4). With this information, a timeline was created for each wing describing the total percent of that wing's population inside the stairwell every 10 s (see Figure 5.12).

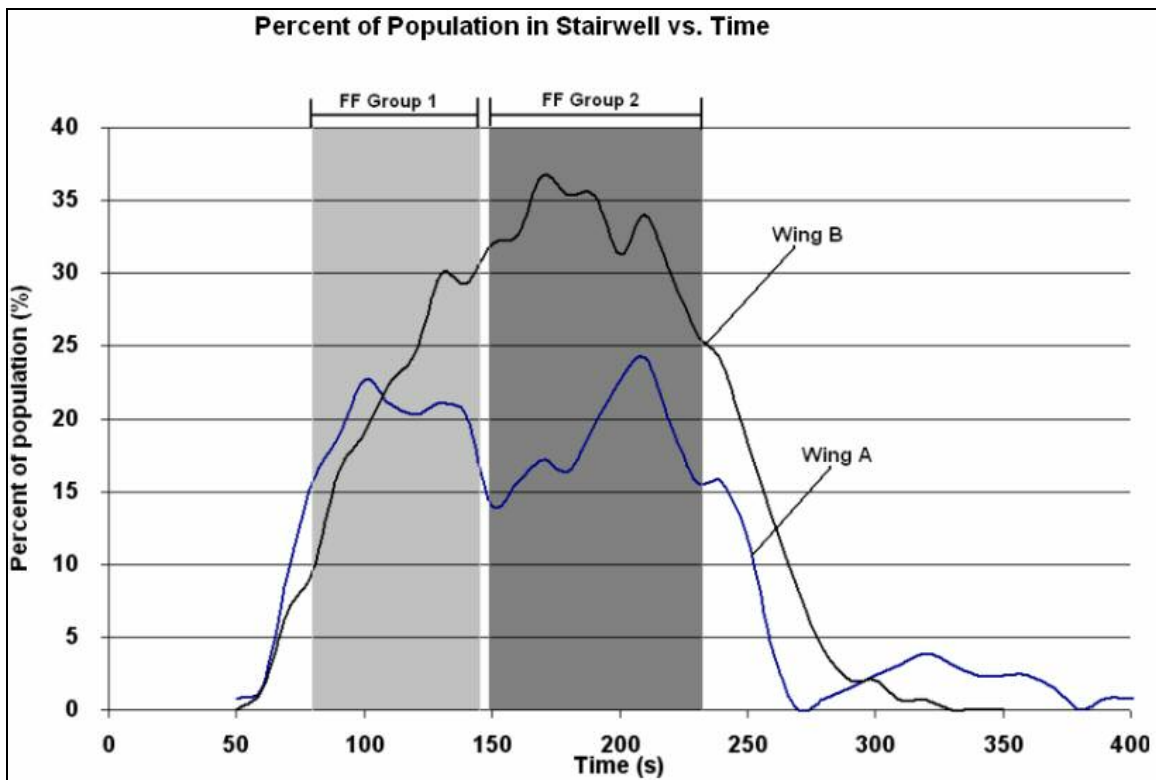


Figure 5. 12 Percent of population in the Stairwell versus Time

The shaded regions in Figure 5.12 indicate the time periods when the two groups of firefighters were in the stairwells. Wing A had significantly less people in the stairwell for the majority of the evacuation. In some cases, the difference was as much as 36 people less in Wing A than in Wing B. It should be noted that Wing B did have more occupants in total travel through the stairwell than Wing A. However, the two wings are still considered to have comparable numbers of people. In Wing A there were 127 people, and in Wing B there were 148 (including firefighters). This is a difference of 21 people. This affected the number of people in the stairwell at any moment, but these 21 people would be expected to be evenly distributed throughout the evacuation. The time period when there was a significantly greater percent of the population in Wing B coincided with the entry and exit of the firefighters. This suggests that the disparity between the two curves was more than just a product of having more people to begin with. The results of Figure 5.12 are significant, and suggest that people were not able to travel in the stairwell as efficiently when presented with counterflow.

In Figure 5.12, the population of both Wing A and Wing B increased at approximately the same rate at the beginning of the evacuation. This suggests that the nature of movement in the two stairwells was similar at the beginning of the drill, with a comparable rate of increase in both wings when the conditions were the same (i.e. before the firefighters entered). Then, when the first group of firefighters entered, the number of people in Wing B continued to increase, and the number of people in Wing A stabilized (at approximately 100 s). Wing A occupants maintained a population within the stairwell at a significantly lower percent of their population than in Wing B. When the second group of firefighters entered, the number of people in Wing B continued to

increase. Wing A's population was also fluctuating at this point in the drill but at a much lower range. It took Wing B approximately 20 s longer than Wing A to reach a population of approximately zero. The individuals that were in Wing A after the time of 270 s were primarily outliers. The reason why Wing A had more outliers than Wing B is unknown. Although their presence was significant, for this analysis the occupant population is considered negligible after 270 s.

Next, the flow rate at the double door exits was considered (see Figures 5.13 and 5.14). Wing A had multiple instances when the exit flow rate reached a value of zero, whereas Wing B never reached such points. The points in Wing A that are associated with a flow rate of zero were due to a lack of supply in people at the exit. Wing B however always had a more constant supply of people at the exit. At the 210 s interval in Wing A there was a collision in the threshold of the double doors when one occupant was holding a cup of coffee and collided with another occupant the moment they traveled through the doors. This incident caused a spike in the flow rate because of the built-up demand for the doorway directly after the individuals recovered from their collision and stepped out of the doorway. The reason for the second spike (260 s) in the Wing A exit flow rate is unknown.

The highest exit flow rate achieved in either wing was caused by the entry of the second group of firefighters in Wing B. The second group of firefighters entered the stairwell later than the first group and when there were more people in the stairwell (see Figure 5.12). Therefore, it is not surprising that the second group of firefighters had more of an impact on the exit flow rate than the first group. The effects of counterflow on exit flow rate do not appear to be as dramatic as the effects on the stairwell overall. Recall

that counterflow more significantly impacted the speeds on higher floors than at F1 (Figures 5.2, 5.3, and 5.4). Moreover, occupants in the counterflow wing were even observed to speed up at the base of the stairwell before exiting (Figure 5.4). This shows that the effects of counterflow were more significant at higher floors than at F1 or the exit. Another interesting point is that the impact of the occupant collision in Wing A on the exit flow rate had almost as much impact as counterflow did in Wing B.

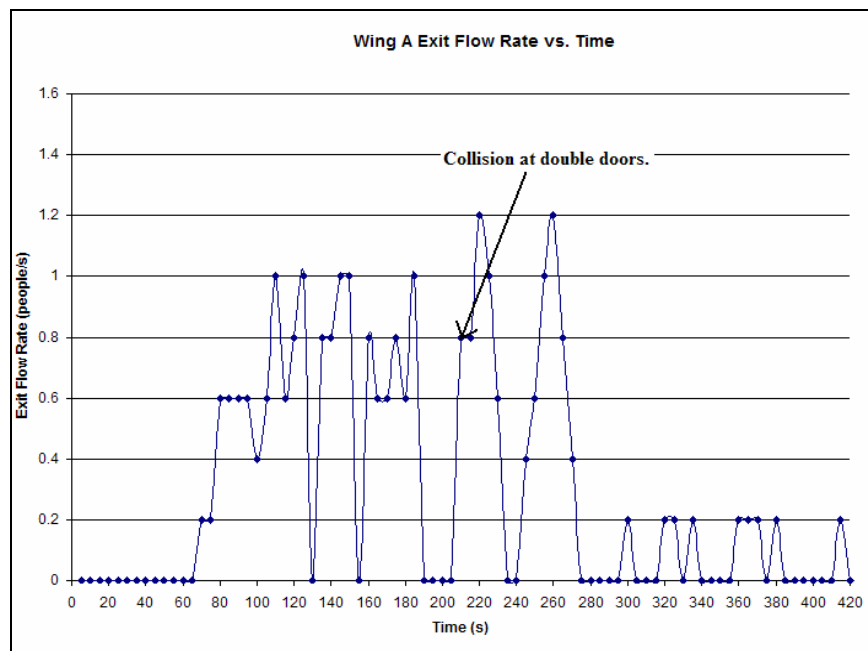


Figure 5. 13 Exit flow rate in Wing A

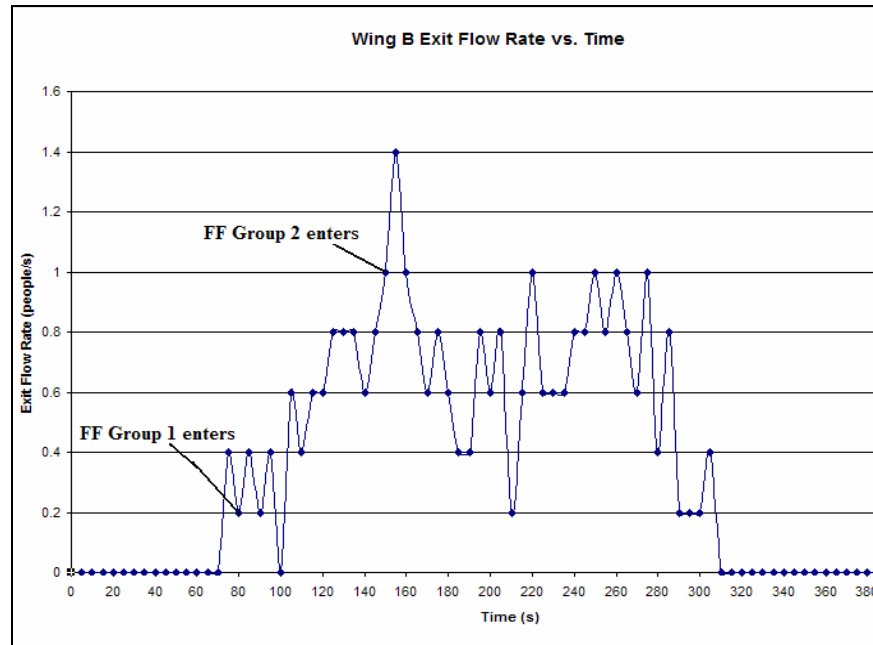


Figure 5. 14 Exit flow rate in Wing B

5.5 Human Behavior

In addition to the three egress parameters (speed, density and flow) this report proposes that there is another variable that can significantly impact the performance of an evacuating population; this variable is human behavior. Traditionally most models make the assumption that speed, flow, and density are interrelated and that the impact of human behavior is assumed to be negligible [18]. This section investigates that assumption.

A key assumption in many models is that, upon hearing the alarm, occupants immediately get up and begin to exit. Essentially, this is the assumption that there is no pre-evacuation movement such as deciding what to do, informing others, or grabbing personal items. To investigate the pre-movement activities of the population, in particular whether people brought personal items with them, every item that each individual brought with them through the evacuation was tracked. If an individual did bring something with them, then there was a greater likelihood that they did not immediately get up and begin to exit the moment the alarm sounded. Furthermore, by

carrying items, especially multiple items or large items one's width could change, which could change the area occupied, and subsequently the density. Also, it could slow people down, inhibit occupants from moving out of the way of the firefighters, decrease their ability to open doors as efficiently, and holding something large may limit their vision of the steps. Moreover, the act of putting on a coat and other clothing articles can affect the duration of pre-movement time. After the analysis was conducted regarding the items carried, the results were categorized by gender to understand if certain types of people in this evacuation were more likely to carry items, and which items they were more likely to carry (for item tracking techniques see to Chapter 4).

Since this behavior was independent of counterflow there is not a distinction between wings for this analysis. Figure 5.15 shows the total percent of individuals who did and did not carry items. Figure 5.16, for the occupants who did bring objects, the items that they were carrying is categorized. There are 11 categories of items noted in Figure 5.16. Primarily, objects that encouraged similar behaviors, or produced similar postures and positions were categorized together. While some of these categories appear to be overlapping, there are important distinctions. For instance, the difference between a backpack and a shoulder bag is that a shoulder bag is held primarily on the side of the body. Even backpacks slung over one shoulder, which lay to a side, are still resting on one's back, whereas a shoulder bag primarily rests on an individual's side or hip, and lower down than a backpack. The difference between the categories of purse or briefcase and shoulder bag is that the purse or briefcase category is considered smaller than a shoulder bag. Some items were categorized in the same category if distinguishing

between the items on film proved to be uncertain, such as a purse or a briefcase⁴.

Another important note is that the total percent of occupants reported in Figure 5.15 and 5.16 add up to over 100% because some occupants held multiple items (this is also true for Figures 5.17 and 5.18). Those who held multiple items were accounted for in all the categories that applied to them, and also reported in the *Multiple Items* category.

A significant finding from Figure 5.15 is that almost half the population was holding something. Also, almost 10% of the overall population was carrying multiple items. Based on the overall frequency of holding items, this behavior was noteworthy and common in this evacuation.

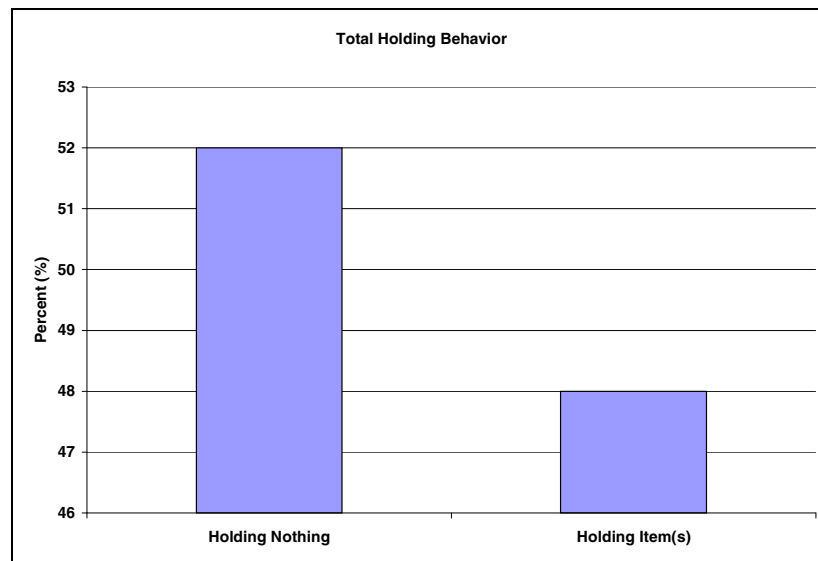


Figure 5. 15 Total percent of population that did and did not carry items

⁴ The importance was to distinguish items that produced similar postures and behaviors', thus distinguishing between a briefcase and a purse was irrelevant as long as the two items were of similar sizes and were held at similar locations on the body.

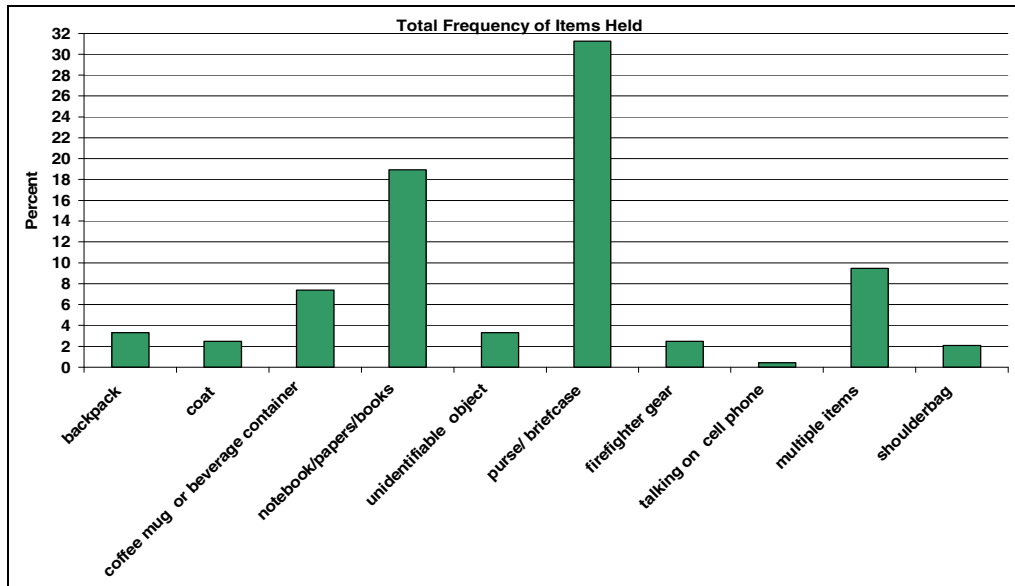


Figure 5. 16 Items carried by occupants

The next behavioral consideration was whether a specific gender tended to gather items more frequently than the other gender (see Figures 5.17 and 5.18). In Figure 5.17 almost 75% of men did not carry anything, while over 75% of women did. Furthermore, 50% of the items women held were purses or briefcases (Figure 5.18). Also, over 10% of the women carried multiple items, while only about 4% of men did. Logically since women brought purses/briefcases over 50% of the time then it was this item that created such a disparity between men and women. The behavior of carrying items, in this drill, is predictable based upon gender; it was also a significant behavioral response in this evacuation.

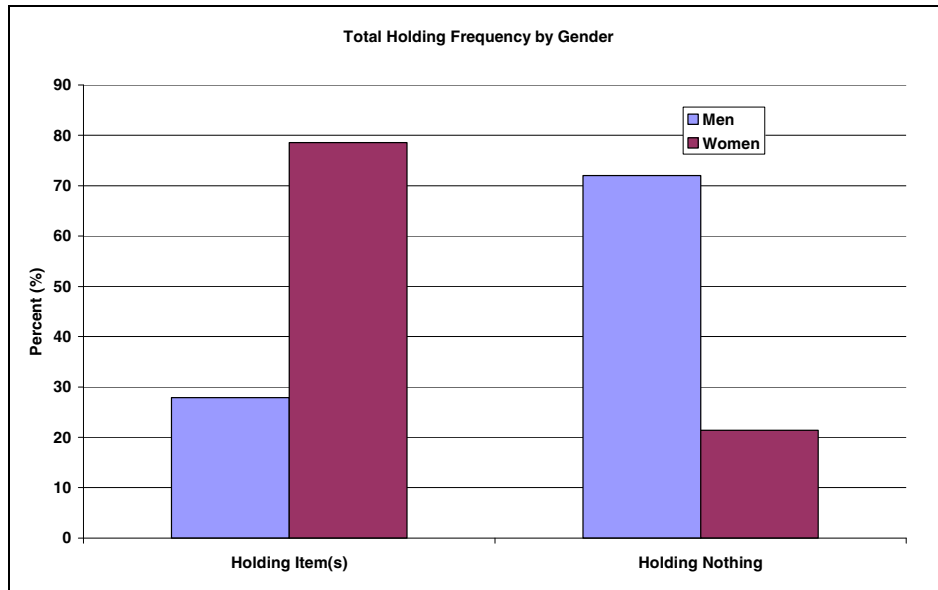


Figure 5. 17 Total holding behavior, by gender

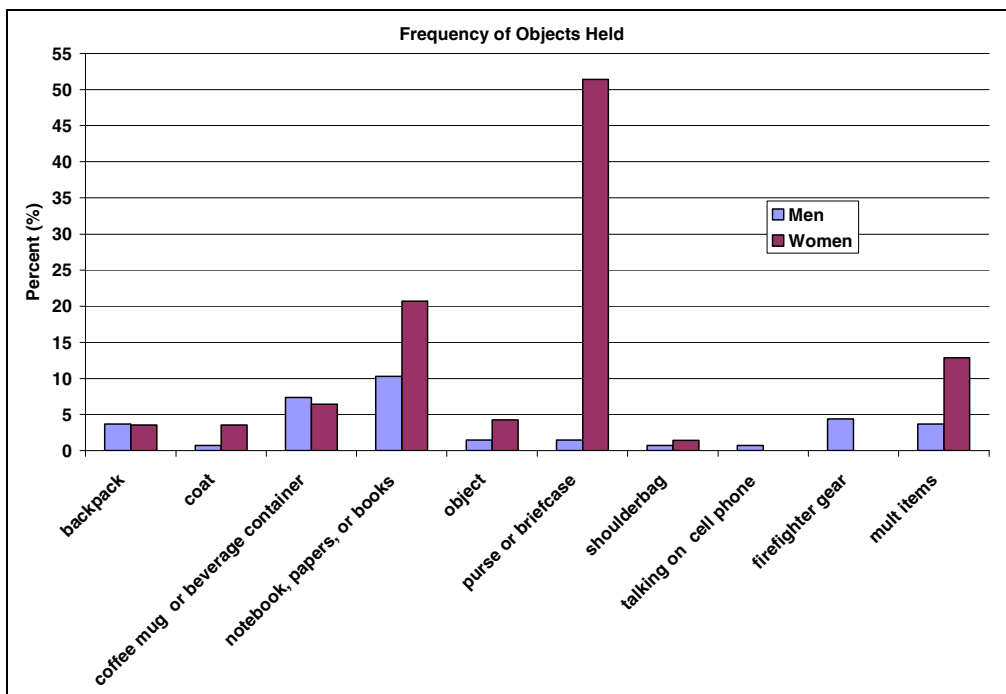


Figure 5. 18 Objects held, by gender

Another behavior observed while evacuating was *over-taking* behavior. In some cases, if there was a very slow occupant and enough room, passing and over-taking occurred to the point where, for brief moments, there were two lanes of traffic: a slow

inner-lane, and a fast-outer lane. It was most commonly observed at the beginning and the end of the evacuation.

The next behavioral aspect studied was exiting behavior. An assumption often made is that by adding double doors (or wider doors) more occupants are able to exit at once. The theory is that the wider the doorway the more people can fit through the door (i.e. an increase in flow rate). Furthermore, by having double doors, as occupants are exiting, firefighters can be entering because there are two distinct lanes of traffic. To investigate whether this type of doorway was truly used by both occupants and firefighters to its full capacity, the door that each individual, in both wings, used when they exited the stairwell was tracked versus time. This provides a map of door usage throughout the evacuation in Figure 5.19. In Figure 5.19, the door being described is on the x-axis, and time is on the y-axis. Each point represents an individual, and their location on the graph represents when they exited and through which door. The letters A and B on the x-axis labels represent the wing, and the designations of left or right correspond to the side of the double door used to exit. All directions are relative to the occupant; thus “Right (A)” means Wing A and the door to occupant’s right. By creating this graphic, it can be determined when the flow switched, and if people were using both sides of the double doors at the same time.

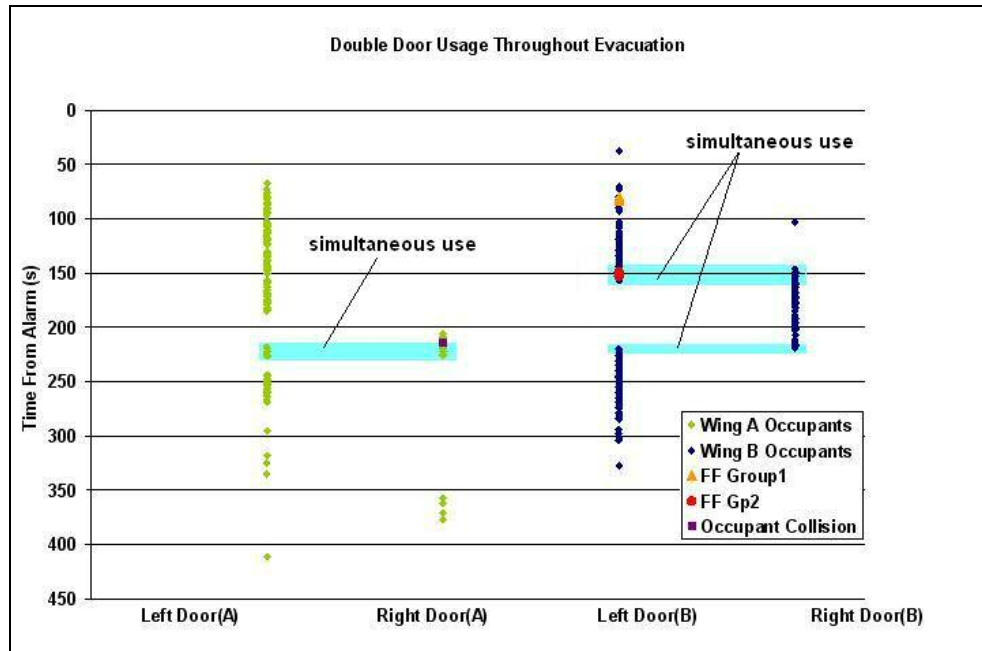


Figure 5. 19 Double door usage

Looking at the timelines for the left and right double doors in Wing A, the vast majority of occupants used the side of the double door to their left in this wing. Furthermore, there was only one instance of occupants using both sides of the double doors at once. There are a few proposed reasons for these behaviors. First of all, by no action from the research team, a trashcan was partially obstructing the right side of the double doors. This trashcan was there upon arrival of the research team. It was left in place by the research team because this was the actual condition of the hallway, and would have been present had the fire drill been a real emergency. However, it was still possible to travel through this side of the doorway even with the trashcan there; it just reduced the available width of that doorway.

There are other behavioral interactions that needed to be considered, which were significant in determining exit door usage in this evacuation. In addition to the reasons just mentioned, another reason that occupants appeared to choose a specific door was

based on where the person before them exited. This was observed by the fast succession of people who traveled out the same door leaf; then when the flow switched the people behind the person who switched it continued to use the same door. For example, in Figure 5.13 at approximately 206 s the flow in Wing A switched from the left door leaf to the right door leaf. Also, there was a gap where no one exited between 185 s to 206 s when the flow switched. Thus, by the time the individual got to the door at time 206 s, the door was completely closed, and also they could not see the trashcan in the way. Therefore, this individual, for whatever reason, decided to use the right side. Then, since there were people behind this individual, they followed each other out the new side of the door. Another important behavior is that occupants rarely shared the doorway, or maintained a lane of traffic in each side of the doorway. Sharing the doorway only occurred once in Wing A and only for a few seconds.

Moreover, sharing the doorway was observed to be complicated by the combination of the trashcan as a partial obstruction, and pre-evacuation activities. Consider the flow switch, at 206 s when people began using the right door (see Figure 5.20). With the new flow pattern, as each person walked out this side of the door they looked at the trashcan in the way as they attempted to open the door fully. Then, someone switched and used the left side also. At this moment people were using both sides of the double doors for the first time in the evacuation at this wing (this and other simultaneous door usages are highlighted in Figure 5.19). However, because the trash can was in the way of the right side there were not two full door lengths for the occupants to share. To further complicate matters, the occupant who used the right side of the double door at 215 s was carrying an uncovered coffee mug. By holding the coffee mug,

this person took up more room in the doorway with his elbow slightly turned out, and the two people collided at 215 s in the threshold of the doorway (see Figure 5.21). After the collision, the occupants switched from using both doorways back to the left side in a matter of 15 s (see Figure 5.22). The collision did cause queuing, which can be seen on Figure 5.13 at approximately 200 s. A drastic decrease and then increase in flow is seen at this point on Figure 5.13. This was a result of the collision causing a stoppage (flow rate was zero) and then the resulting queuing behind the collision causing a rise in flow rate.

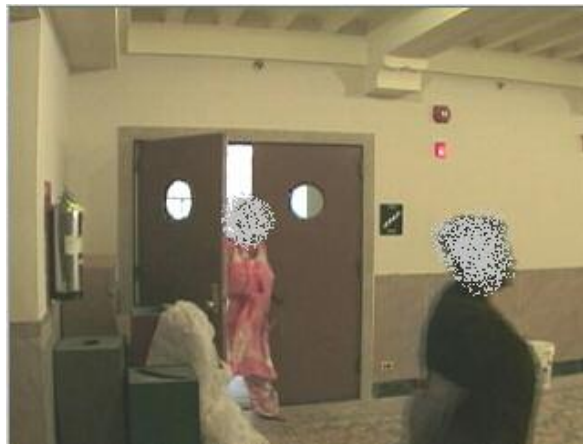


Figure 5. 20 Flow switched to the right side of the door at $t=206$ s



Figure 5. 21 Occupant collision in Wing A at $t=215$ s



Figure 5. 22 Flow switched back to left door at t=230 s

This was an important incident in this evacuation. First, it showed that such unforeseen events, such as a blocked exit, affected movement in this evacuation. Second, occupant behavior affected the speed and flow rate of the population. Not only did taking the beverage cause the person to occupy more space in the doorway, but it also caused an incident in the doorway. Had the situation been less tenable or had the collision been more serious (i.e. spilled drink, injury, etc.) a pile-up at the doorway could have occurred rendered the entire stairwell useless. Current evacuation models could have captured the nature of a blocked exit, but they may not have accounted for an individual who was carrying an object or that this behavior could further complicate the movement of evacuating. Another significant finding is that it was more common in this evacuation to follow behind someone when exiting; in which case the use of double doors to increase exit capacity would not have been effective for this evacuation. Decision making by the occupants was a fourth important parameter of egress for this evacuation that influenced, and was influenced by speed, density, and flow rate.

Next, consider the double door usage in Wing B. Since this was where both the firefighters entered and the occupants exited, some interesting questions are raised. From Wing A it was the theory that occupants seemed to use only one side of the double door at a time. In that case, certain circumstances made them favor the left door. However, it is hypothesized that even though one door was partially blocked that this tendency would still have been present even without the blockage because of the following tendency observed. This can be tested in Wing B. Another important consideration is whether the firefighters used one side of the double doors and the occupants used the other. This would have been an efficient use of the double doors since these groups were moving in opposite directions.

From Figure 5.19 the occupants followed the pattern of essentially using one side of the double doors at a time. This confirms the tendency in the Wing B evacuation that was suspected in Wing A. There were two times when the flow switched in Wing B: the first was at 157 s and the second was at 219 s. The first switch occurred directly after the second group of firefighters traveled through the doors. It is striking that both of the times the groups of firefighters entered they did so at the same side of the double door that the occupants were flowing through. The first group of firefighters entered at a point when the density of occupants was low enough that their opposing motion did not interfere with egress (i.e. the flow does not switch door sides). The second group of firefighters actually forced the flow of occupants to switch to the other side of the double doors (see Figure 5.23). What is noteworthy is that the firefighters choose this side to travel through when the other side of the double door was not even being used. In Figure 5.23 Person A is about to move through the door to his left, and Person B can be seen

through the window on the other door as queued to move through the left side of the door also. Note that there was queuing and still the occupants did not move through both sides of the doors. Then, at time 148 s the firefighter (FF 2.1) can be seen as he moves through the queued side instead of the opposite side. When he does that, Person A is forced to move to the other double door side even though he has almost moved all the way through the doorway. Then person B, who was queued at one side, must switch sides also. By 149 s the flow switches to the right side of the door completely as a result of the firefighters. Therefore, firefighter counterflow and their behavioral interactions with the occupants caused this flow switch.

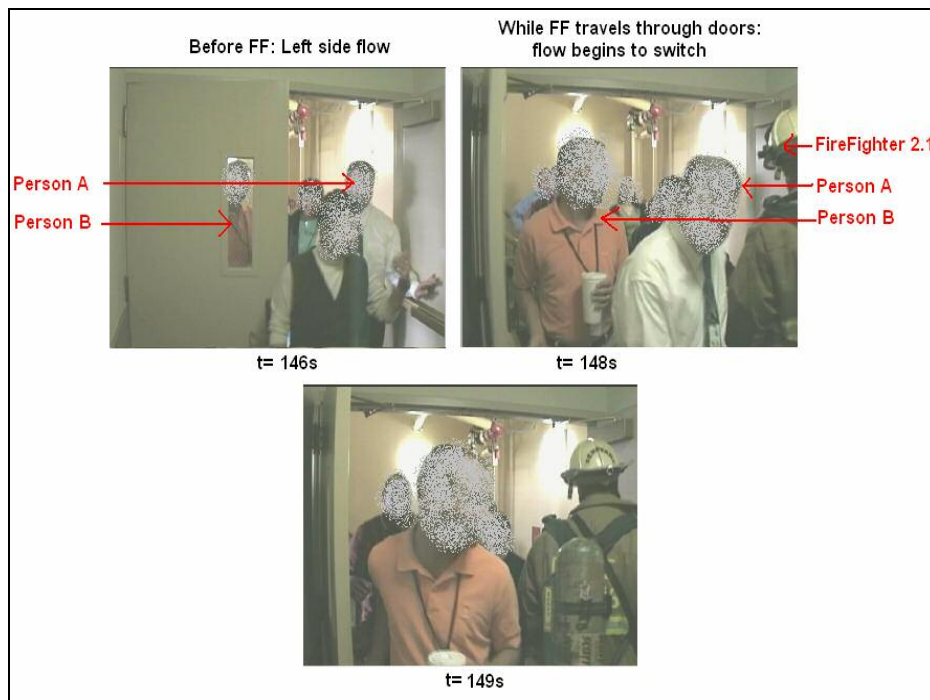


Figure 5. 23 Firefighters traveled through same side of double doors as occupants

The second time there was a flow switch at the Wing B double doors was at 219 s. At this point the door flow switched back to the left side. It is unclear what event initiated the switch.

Going back into a building during an evacuation is a behavior that is nonadaptive. An incident that significantly affected the flow rate in Wing A was when a group of six occupants performed a series of nonadaptive behaviors. These individuals entered the Wing A stairwell and then turned around and re-entered the building. Eventually the six occupants of the group all reappeared and exited. It took up to one minute for everyone in the group to reappear, and resume evacuating. It is unclear why they went back into the building. However, this group of people performed a significant series of nonadaptive behaviors in the drill because they were functioning as a group of individuals making decisions together. Furthermore, this group actually stopped on the stairwell landing to have a discussion both before and after re-entry (which blocked the stairwell for others), and as a group, they left the stairwell together. The action of one person in the group having gone down the stairs, and then back up also created minimal levels of counterflow at this floor.

To detail this event further the timeline is as follows:

This occurred at peak travel time, beginning at approximately 2 minutes. One group member entered the F5 landing from inside F5, and five people entered this landing from F6 above. Five of the people then exited the protected stairwell and went back into F5 of the building, and one person continued down the stairs. However, before the five people re-entered the building they had a discussion on the landing. While they had their discussion, other evacuees were maneuvering around them. When their conversation was completed they re-entered the building at F5 and then it took approximately 1 minute for all occupants to return to the F5 stairwell. The only person who did not re-enter the building with the group members was the person, who before

traveled down the stairs (she traveled one floor down to F4 before turning around). She traveled back up and met her group members as they returned to the stairwell. In order to reach her group members she held the door open for a significant amount of time, because there were other people flowing out. Then, when she saw her group coming out of the door she held the door for them and then turned around again to travel back down. Then the entire group had a discussion and as a group all of these individuals traveled down the stairs. At this point they were traveling towards the end of the evacuation. Making an assumption that occupants do not think, in the case of this evacuation, is dangerous since the occupants not only made personal judgments but there were instances when they made judgments as a group.

This incident also highlights another frequently observed behavior: door holding. Holding a door open and waiting for the next person to reach it was observed in both wings. The most frequently observed time to hold a door was for 4 s. It is interesting to note the lack of urgency associated with this behavior, and how certain levels of politeness and etiquette were still maintained even in the potential emergency. Altruism is a common response that has been observed by other researchers in both drills and real emergencies as well [12].

There were other non-adaptive behaviors observed in Wing A including a male occupant who exited at the very end of the evacuation. He was carrying a large backpack and stopped in the middle of a landing in the stairwell, put his backpack on the ground and riffled through it for 6 s. There was also a trained security guard in Wing A that entered the stairwell at F1, at the beginning of the evacuation, and traveled to F3 and re-entered the building. Re-entering the building was not an instruction given to the security

guards. This individual did create minor amounts of counterflow. This occurred towards the beginning of the drill and not at peak levels of occupants in the stairwell.

The next behavioral observation to note is the fact that there were significantly more nonadaptive behaviors in Wing A. At no point in Wing B did an occupant travel back up the stairwell, or re-enter the building. There were occupants in this wing that did perform such behaviors as talking on the cell phone, but in many ways this behavior is less nonadaptive than actually leaving a protected area. The reason for the difference in the wings is hard to surmise since this set of data is only from one case.

5.6 Speed Based on Gender

The frequency of overall speeds is considered by gender (see Figures 5.24 and 5.25, and Table 5.2). There was not a noteworthy difference between the speeds of each gender. In this case, it appears that gender is not as good of a predictor of speed as density. Thus, the wing an individual traveled in is a better predictor of speed than gender.

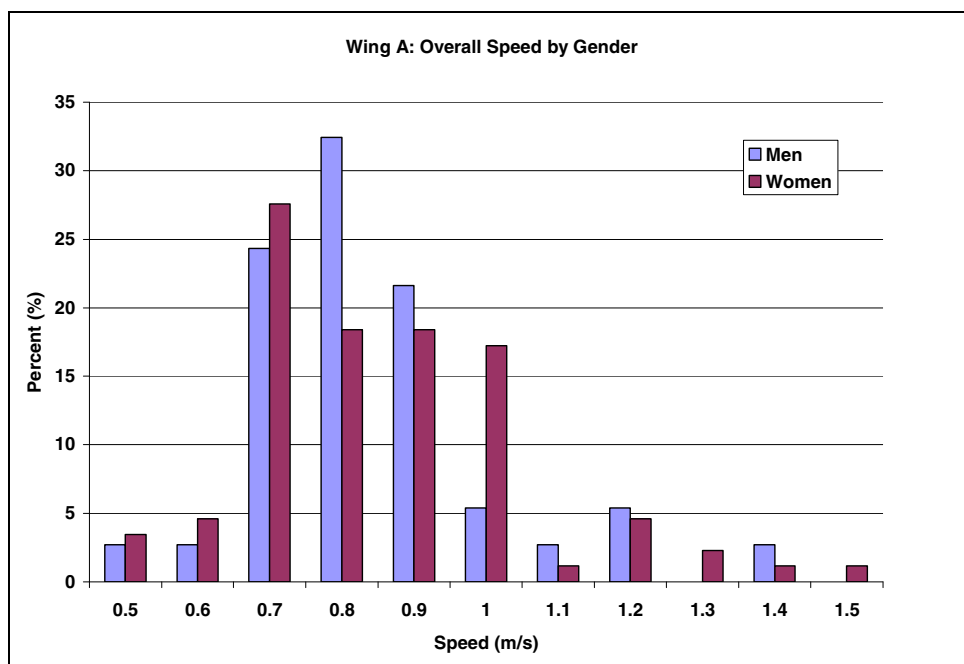


Figure 5. 24 Wing A overall speed based on gender

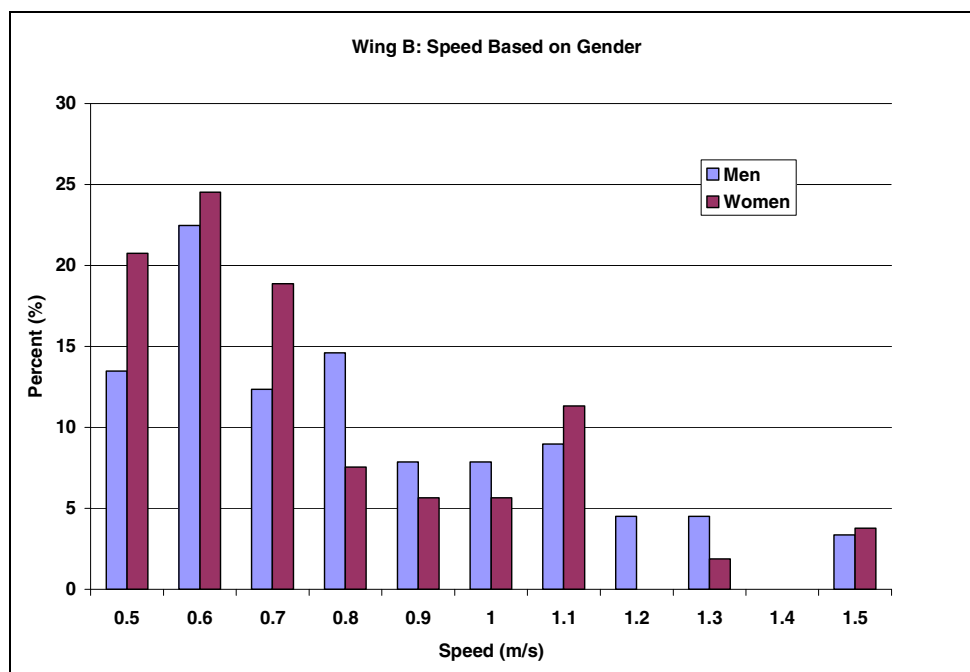


Figure 5. 25 Wing B overall speed based on gender

Table 5. 2 Average overall speed for men and women in each wing

		Average Overall Speed
Wing A	Men	0.81
	Women	0.80
Wing B	Men	0.76
	Women	0.70

5.7 Behavioral Responses to Firefighters

It is important to note the population's behavioral response to seeing the fully geared firefighters. The most significant behavior that was observed in this evacuation when the firefighters passed the individuals was an impulse to stop. Even in instances of low densities, the occupants generally attempted to move out of the way and then stopped in place. This behavior is somewhat analogous to pulling a vehicle over to the side of a road when an emergency vehicle passes. The location in the stairwell where the occupants "pulled over" was different at each camera location, and depended directly on the directions of the firefighters.

Surprisingly, firefighters did not give the occupants consistent directions on each floor. In addition, each firefighter group often gave different directions. Since both groups, in some cases, passed some of the same occupants, these individuals received different directions from different groups of firefighters, and on different floors. Mainly, the firefighters instructed the occupants to move to the right, but sometimes they told them to simply move out of the way (i.e. no direction given). Furthermore, sometimes the firefighters traveled to the occupant's left and sometimes they traveled in the middle of the stairwell. Table 5.3 provides an overview of the directions given to the occupants by the firefighters.

Table 5. 3 Firefighter directions to occupants

	Firefighter Group 1	Firefighter Group 2
F1	"Stay right!" (Softly spoken)	"Stay to the right! Firemen coming up!"
F2	"Move out of the way."— (i.e. no direction given)	"Stay to the right!"
F3	"Stay right!"	No directions given.
F5	FIREFIGHTER EXIT FLOOR	

It should be emphasized that the firefighters were not given any instructions of any sort on how to ascend the stairwells, or what instructions to give to the occupants. As a result of the conflicting directions two completely different conditions were produced in stairwell. In Figure 5.26 the occupants, after being told to move to the right by the first group of firefighters, are lined up in an orderly manner on the inner-lane of the stairwell at F3.5. The stairwell was crowded, but there was order to the area, and the firefighters were able to move up the stairwell even with a large high-rise pack over one shoulder. In Figure 5.27, occupants at F3.5 were not given instructions by the second group of firefighters, and are all over the stairwell. There were also noticeably different in body positions. In Figure 5.26, all occupants are facing with their entire bodies forward. Furthermore, in Figure 5.26, the firefighter pictured has his body completely forward. However, in Figure 5.27, in order to allow the firefighter to pass by, the occupant in the bottom left corner of the picture is turned completely sideways. Also, it appears that the firefighter pictured also has to turn partially sideways to maneuver around the occupants. Turning one's body sideways is an action used when there is not enough room. It is an attempt to make more room for, in this case, the firefighter to pass

by. These conditions were typical of that observed on all the floors with the different instructions.



Figure 5. 26 Example: FF Group 1, instructed occupants to move to the right (F3.5)



Figure 5. 27 F3.5, Example: FF Gp 2, occupants not given directions (F3.5)

From this comparison, and other similar incidents in this evacuation, the instruction given to the occupants to move to the right was observed to create a more orderly evacuation, and in essence reduced some of the effects of counterflow by creating a lane for the opposed flow to travel in. This of course, was subject to density. When the density in the stairwell was so great that there was no room for a right and left lane, then

these instructions were less effective. Since the stairwells in this building were wide enough, this was not generally an issue in this evacuation. However, in this building, when instructed to move to the right there was a few cases where the occupants attempted to move in a single file line on the inner part of the stairwell and there just was no room for an individual. This usually resulted in the individual turning completely sideways in order to allow the firefighter to pass by them. An example of this occurring is presented in Figure 5.28 below.



Figure 5. 28 Example: man must contort body sideways to let firefighter pass.

Even though the man highlighted in Figure 5.28 has been instructed to move to the right by the firefighters, as people began to move over there was no space for him. As a result he was forced to turn completely sideways to let the firefighter pass. This is an extremely inefficient motion, and it is one that if the stairwell was narrower or there were more people in the area, he may not have been able to complete. Furthermore, this movement required the individual to stop or slow down more than if he could have just moved over and kept walking. There was also the possibility of tripping. Therefore,

even in instances when people were given consistent instructions they would only have been effective if the density of the stairwell could have accommodated the instructions, or if the width of the stairwell was wide enough.

Chapter 6: Discussion

6.1 Introduction

The purpose of this chapter is to take the results, and hypotheses presented in Chapter 5 and compare them to the literature presented in Chapter 2. Both qualitative and quantitative results were compared.

6.2 Speed

In addition to the model derived from Pauls' data, and reported in Chapter 5, Predtechenskii and Milinskii's model for determining speed has been compared to the current studies' findings. Recall from Chapter 2 that Predtechenskii and Milinskii's model for determining speed down stairs is as follows:

$$v_{down} = v \times m_{down} \text{ (m/min)} \quad \text{Equation 2.4}$$

Where:

$$m_{down} = 0.77 + (0.44e^{(-0.39D)})(-0.39D)\sin(5.61D - 0.224) \quad \text{Equation 2.5}$$

$$v = 112D^4 - 380D^3 + 434D^2 - 217D + 57 \quad \text{(m/min)} \quad \text{Equation 2.6}$$

$$D = \frac{\sum f}{\delta l} \quad \text{Equation 2.7}$$

f = The area of horizontal projection for each person (m^2)

δl = Area of density area (m^2)

In the case of this evacuation, an f value for adults dressed in "mid-season street dress" was chosen [6]. This type of dress was chosen because it was the most consistent with the attire for the drill. Occupants were not wearing winter clothing or heavy coats, and although it was the summer occupants were not observed to be wearing clothing

typical of the summer, such as shorts, since they were dressed in business attire. Thus, using this f value (0.113 m^2) and the total number of people in the density area at each of the ten second intervals, the density was determined using Equation 2.7. Since everyone in the density area was assumed to have the same f value, Equation 2.7 at each time interval became:

$$D = \frac{(0.113 \text{ m}^2)N}{\delta l} \quad \text{Equation 6.1}$$

Where:

N = Total number of people in the density area at a given time interval.

δl = Area of density area (m^2)

Next, using these density values, speed through the density area was determined using Equations 2.4 through 2.6. Then these calculated values for travel speed, as predicted by Predtechenskii and Milinskii's model, were compared to the values actually observed.

Figures 6.1 and 6.2 provide the experimental velocities as a function of density, as well as the predicted velocities using Predtechenskii and Milinskii's model. Since the current study and Predtechenskii and Milinskii's model used different definitions of density a conversion between the two needed to be determined. Recall that the current study's definition of density is:

$$D = \frac{N}{\delta l} \quad \text{Equation 6.2}$$

Where:

N = Total number of people in density area at given time interval

δl = Area of density area (m^2)

Since the densities determined using Predtechenskii and Milinskii's model (m^2/m^2) are correlated to this report's definition (people/m^2) by a factor of 0.113, comparisons between the two definitions of density was made using this as a conversion factor (Figures 6.1 and 6.2 are reported using this report's definition of density, people/m^2). Moreover, to allow both studies' definition of velocity to be compared Predtechenskii and Milinskii's model was converted from meters/minute to meters/second.

Also reported is the curve presented in Proulx's chapter of the SFPE Handbook, based on Pauls' data. "Linear (Wing A/B Occupants)" in Figures 6.1 and 6.2 refers to the linear curve fit for the Wing A or B occupant dataset; "PM correlation" refers to Predtechenskii and Milinskii's predictions; "SFPE correlation" refers to the correlation in Proulx's SFPE Chapter based on Pauls' data that was originally presented in Chapter 5.

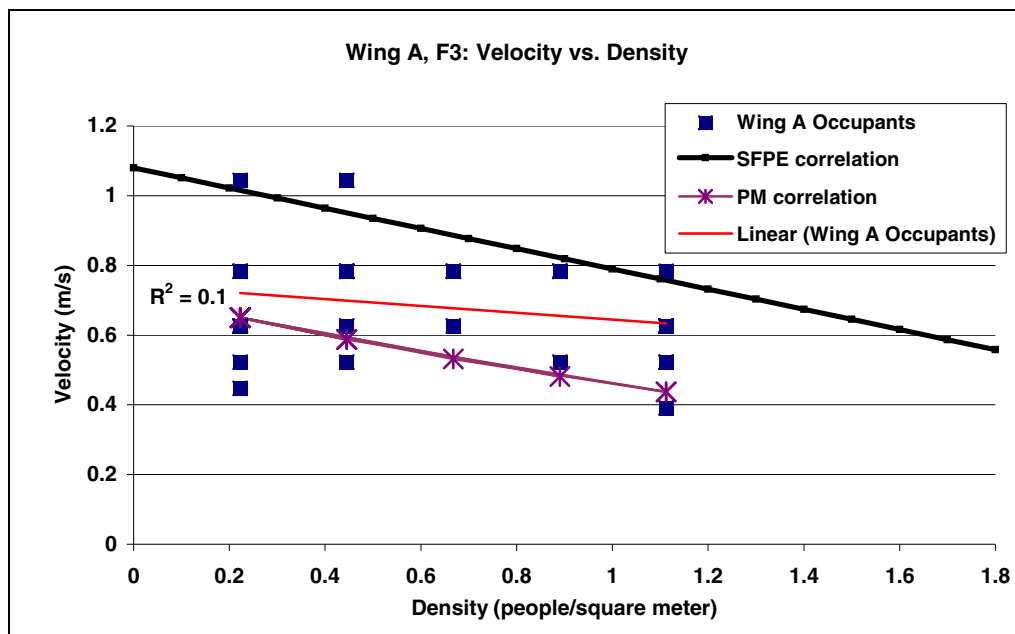


Figure 6. 1 Velocity down the stairs versus density in Wing A

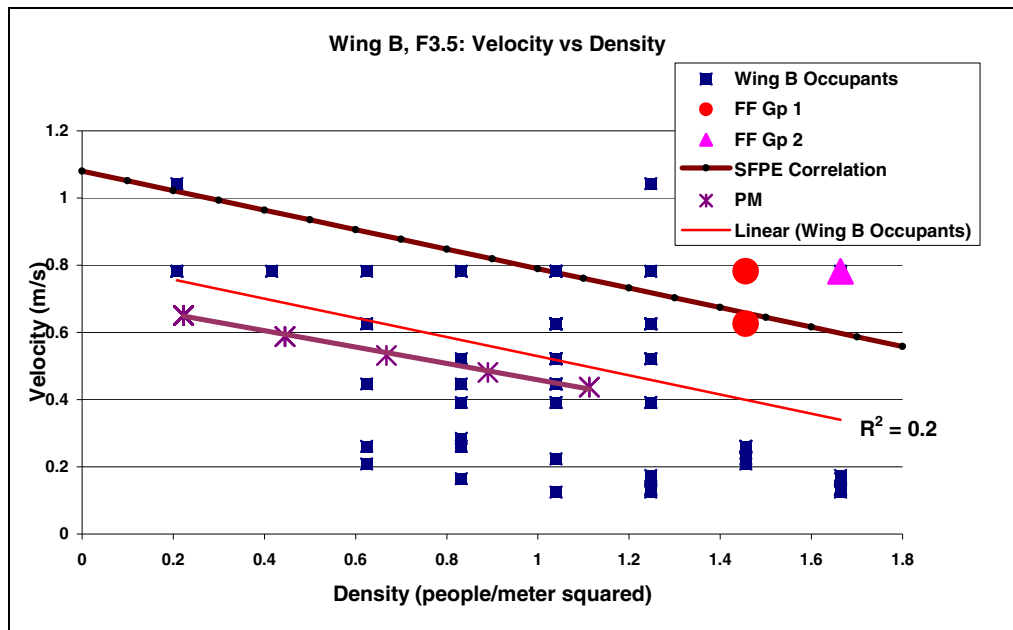


Figure 6. 2 Velocity down the stairs versus density in Wing B

In Figures 6.1 and 6.2 the occupants observed by Predtechenskii and Milinskii, and their corresponding models are a reasonable predictor of the velocities observed in this evacuation. However, their data seems to predict the Wing B velocities better than the Wing A velocities. Predtechenskii and Milinskii's correlation also predicts both wings' speed better than Pauls' model, especially Wing B. This shows that, the occupants in their study traveled at a slower pace than those in Pauls' study, and that the slower pace characterizes the occupants in this drill better.

Another significant source of data about speed in stairwells is the research conducted by Fruin. Fruin characterized speed for different age groups, and genders in his study. Occupants in the age category of 30-50 years old were compared to the occupants of the current study. For men in this age category, the average speed reported by Fruin was 0.65 m/s. For women, the average speed in this age category was 0.5 m/s. This finding compares better to the Wing B findings than the Wing A findings. Recall

from the overall speed calculations in Chapter 5 that 50% of Wing B traveled between 0.5 and 0.6 m/s. In Wing A, 50% of the population traveled between 0.7 and 0.8 m/s. The stairwells observed in this evacuation were wider than typically experienced, which created more travel area (i.e. lower density). Thus, it is significant that in a narrower stairwell (as observed by Fruin) the average speed was found to be similar to a wider stairwell *with* counterflow. Thus, in this evacuation, the counterflow was essentially narrowing the stairwell, and increased the density for the evacuating population.

In the study by Kagawa, Kose, and Morishita, speed was measured by noting the time spent per floor. They observed occupants exiting a 53-story high-rise office building in Tokyo [8]. They reported that for occupants who they believe entered the stairwell at F3 (i.e. they only traveled through a total of three floors and then reached the exit) they reported an average descent time of 42 seconds [8]. In the current study, the average descent time for those first seen on F3.5 in Wing B was 56 seconds. The average descent time for those who were first seen at F3 in Wing A was 36 seconds. What is noteworthy is that the average of Wing A and Wing B (46 seconds) was approximately the same as observed by the Japanese researchers. However, it is important to remember that those in Wing B traveled an extra half floor since their times were measured at half floors. So the average value of Wing A and Wing B (46 seconds) is expected to be a few seconds lower.

Furthermore, the Japanese research team noted that the average speed was between 16 and 20 seconds per floor [8]. Note that in their study there were as many as 53-stories for some occupants to traverse. Therefore there were other factors that were presented to the Tokyo office-building population, then the population in this study, who

only had to travel down as many as 6 stories. For instance, those who entered high up in the 53-story building were more likely to have experienced fatigue. Therefore it would be expected that the occupants of the Japanese study would, on average, have spent more time per floor than those in this study. Tables 6.1 and 6.2 describe the average descent time per floor, based upon the floor first seen on. By dividing occupants up by floor first seen it is inferred whether those who entered higher up in the building, on average, spent more time per floor than those who entered on lower floors.

Based on the findings in Tables 6.1 and 6.2, even in this building where there were only 6 floors, it can be seen that the higher up an individual entered the stairwell, the more time they spent per floor on average. In Wing B, the effects of counterflow are seen because at F2 (Wing A) and F2.5 (Wing B) the average descent time per floor was the same in both wings, but at above floors the difference between the two wings grew. However, the average descent time overall for each wing was only 2 seconds longer in Wing B. Also, as expected, both wings in this building were slightly faster than the minimum travel time per floor reported in the Japanese study. The participants of the current study were in some cases 25 to 30 percent faster than the Japanese study, but since the building observed in the Japanese was over 8 times taller, this is as expected. If the occupants of the Japanese study maintained a pace as fast as occupants who traveled a maximum of six flights of stairs that may have been a suspicious result. Therefore, it is concluded that the Japanese study and this study have comparable findings, although this is considered a rough comparison.

Table 6. 1 Average descent time by floor for Wing A

Ave. Decent Time by Floor First Seen	Decent Times per Floor
Floor level	Seconds
2	8
3	12
5	14
Average:	11

Table 6. 2 Average descent time by floor for Wing B

Ave. Decent time by Floor First seen	Decent Time per Floor
Floor Level	Seconds
1.5	8
2.5	8
3.5	16
5.5	21
Average	13

At Lund University, Frantzich studied stairwell movement by filming volunteered subjects as they traveled through different types of staircases. He concluded that 0.7m/s was the mean travel velocity of the test subjects [9]. This agrees with the results found in this study. With counterflow, the majority of the population in the current study traveled between 0.5 and 0.6 m/s, and without they traveled between 0.7 and 0.8 m/s. Therefore this value is within the same range determined in this study.

For counterflow conditions, Holmberg's investigation of motion on different egress components provided a source of comparison for this study. The results of Holmberg's study and the current one are remarkably alike. Holmberg's study shows that speed was slightly slower with counterflow, generally by 0.2 m/s [16]. In the current study, with counterflow there was a relative difference of between 0.1 to 0.3 m/s slower,

which is the same result that Holmberg achieved on sidewalks. Remarkably, the two studies, regardless of the egress component, produced the same results. According to both the sidewalk case studied in New Zealand, and this particular evacuation case study, counterflow made a small but noticeable difference in the average speed achieved by the population.

Navin and Wheeler also studied counterflow on sidewalks. They concluded that where no counterflow was present occupants achieved a speed of 1.4 m/s [15]. The researchers found that this was greater than the pedestrians in counterflow conditions ever achieved [15]. Occupants in the current study traveled slower than 1.4 m/s because Navin and Wheeler studied a horizontal component, versus a staircase, which requires more concentration (see Chapter 2) [5]. Therefore it is not surprising that the speed capabilities, even without counterflow, are less than Navin and Wheeler found. The one aspect that both studies have in common is that in the current study Wing B did not generally reach the speeds of Wing A.

In summary, it should be emphasized that, a portion of these studies agreed more with the results for the wing with counterflow than the wing without. This is because many of the studies mentioned primarily were based on observational data from narrower stairwells. Thus, in a narrower stairwell with no counterflow, the results were similar to a wider stairwell with counterflow (see Table 6.3), because the counterflow was essentially narrowing the stairwell for the evacuating population.

Table 6. 3 Summary of comparison results for population speed

	Type of Study	Results
Pauls' model in SFPE Handbook	Movement down stairs.	Over-predicts speed of the population in this study at different levels of density.
Predtechenskii and Milinskii	Movement down stairs.	Reasonable predictor of speeds achieved at different density levels in the current study. Better predictor <i>with</i> counterflow.
Fruin	Movement down stairs.	Good predictor of the average speed achieved in the current study. Better predictor <i>with</i> counterflow.
Kagawa, Kose, and Morishita	Movement down stairs.	Good predictor of average speeds achieved in current study.
Frantzych	Movement down stairs.	Good predictor of average speeds achieved in the current study. Better predictor <i>without</i> counterflow.
Holmberg	Counterflow on sidewalks.	Same results in both studies, a difference of 0.2 m/s with counterflow.
Navin and Wheeler	Counterflow on sidewalks.	Similar results, and trends in both studies.

6.3 Flow Rate

Recall from Chapter 2, that the *Effective Width Model* by Pauls was introduced. His model is based on data that relates the effective width of the stairwell, the number of persons that evacuated, and total flow time. Using his equation (Equation 2.1 in Chapter 2), and based on stairs that have 7.0 in risers and 11 in treads (as was most similar to the stairs this study), the data from the current study was applied to his model. Given the effective width of the stairwells and the total evacuation times, the number of people predicted using this model has been determined and compared to the actual number of people that traveled through the stairwells in the flow time. This analysis was conducted using Pauls boundary layer widths, and not boundary layers that were actually measured

in this drill. Measuring the boundary layers that the population in this study maintained is a topic for future research.

Wing A: To predict the number of people that evacuated using Pauls' Effective Width Model, the first step was to find the W/P for Wing A:

$$\frac{W_A}{P_A} = 8040T_A^{-1.37} \quad \text{Equation 2.1}$$

$$T_A = (t_{A2} - t_{A1}) = 411 - 56 = 355 \text{ s}$$

t_{A1} = Time first person enters stairwell (s); t_{A2} = time last person leaves stairwell (s)

$$\frac{W_A}{P_A} = 2.58 \quad \text{Equation 6.3}$$

[4]

According to Pauls, an adjustment to W/P must be made if the riser exceeded 180 mm.

Since the stairs in this wing had 203 mm risers, an adjustment was necessary. He suggests “adding 1 percent to W/P for every 5 mm that the riser exceeds 180 mm” [4].

Therefore 4% was added to the W/P in Wing A:

$$\left(\frac{W_A}{P_A} \right)_{ADJ} = 2.68 \quad \text{Equation 6.4}$$

Based on this value of $\left(\frac{W_A}{P_A} \right)_{ADJ}$ and the effective width:

$$P_A = \mathbf{526 \text{ persons}} \quad \text{Equation 6.5}$$

[4]

Thus, according to the Effective Width Model in 355 seconds, in a stairwell that is 1410 mm wide, 526 people are predicted to be able to evacuate. In the actual observed evacuation, 128 people were seen to evacuate through this stairwell in 355 seconds. It should be emphasized that Pauls' model predicted the number of people that *could* have exited at the *stairwell's capacity*, whereas the Wing A stairwell was not used to capacity (based on density results and the judgment of the building staff). However, the point of this calculation is that Pauls model predicted over four times as many people could possibly evacuate as were observed. It is unlikely based on the density results for the stairwell to assume that the stairwell in the current study was only used to a quarter of its capacity. Furthermore, even without planned counterflow this stairwell still experienced nonadaptive behaviors, collisions between occupants, spikes in flow rate, and other conditions assumed not to occur in Pauls' model. If any one of these events were to be considered in this model it raises the question as to whether the model would hold true. Therefore, one can say it may be *possible* to have had 526 people evacuate from this stairwell, had it been used to its maximum capacity, and with no other outside factors such as human behavior. Therefore the results of Pauls model must be used with caution for this evacuation since this is an idealized figure.

Now the same procedure was used to determine the number of people predicted to evacuate from Wing B, compared to the number of people observed to evacuate.

Wing B: As before, the first step was to find the W/P for Wing B:

$$\frac{W_B}{P_B} = 8040T_B^{-1.37} \quad \text{Equation 6.6}$$

$$T_B = (t_{B2} - t_{B1}) = 411 - 56 = 355s$$

t_{B1} = Time first person enters Wing B stairwell (s); t_{B2} = time last person leaves Wing B stairwell (s)

$$\frac{W_B}{P_B} = 3.73 \quad \text{Equation 6.7}$$

[4]

Since the stairs in this wing had the same tread and depth as Wing A, 4% was added to the W/P as an adjustment in Wing B as well.

$$\left(\frac{W_B}{P_B} \right)_{ADJ} = 3.89 \quad \text{Equation 6.8}$$

Now, based on the $\left(\frac{W_B}{P_B} \right)_{ADJ}$ and the effective width, P_B is **360 persons**.

According to Pauls' model 360 persons are able to evacuate Wing B in 271 seconds and with an effective width of 1397 mm. Again, this is a minimum time to evacuate 360 persons because its assumed that there was a constant supply of people, the stairwell was used to capacity (but not above), and that there were no delay times. Wing B had a total of 142 occupants exit through the stairwell. This model predicts that over two and a half times more people could evacuate, and it is unlikely to assume that Wing B was filled to less then half of its capacity. This assertion is based on the density results of this report and the judgment of the building staff. While this stairwell had points where it was not completely filled (i.e. not filled to capacity), there were instances of high densities, stoppages, and other behaviors associated with high stairwell densities. Thus, it is possible that more people *could* have evacuated, however since there were already high density behaviors present it is unlikely over two times more people could have safely traveled through the stairwell.

As with speed, in Chapter 5 a model for flow rate as a function of density was presented with the data. This model is based upon an observational study by Pauls (different than his Effective Width Model). Recall that using this model predicted a higher flow rate than was actually observed in the data at most densities, and in both wings. This meant that those observed by Pauls were capable of achieving a higher flow rate than those in this evacuation. Thus, Pauls introduced two models for flow rate, and the assumptions of both of these models should be understood thoroughly before applying them. For example, these models assume there are no delay times, but since approximately 50% of the population in this evacuation was observed to carry at least one object with them in the evacuation it is likely that a pre-evacuation delay time was involved in grabbing an item before evacuating.

In Kagawa, Kose, and Morishita's study they noted that there were stoppages in the stairwell for up to 10 to 15 seconds to wait for congestion to clear [8]. In their study there were no planned opposed flows, or blockages, but with such a large amount of floors to traverse (up to 53-stories) the occupants encountered standstills from blockages that originated on floors below. The researchers noted that these sorts of stoppages are "highly probable" [8] from their results, and that a standstill in the stair may appear if 3 or 4 neighboring floors were evacuated at once [8]. In the current study, where there were only six floors total, stoppages and congestion were magnified by the presence of counterflow. Stoppages in the current study ranged from 5 to 12 seconds, and generally occurred when the occupants were moving out of the way of the firefighters. Wing A encountered very little stoppages. Thus, in a building with relatively few floors, stoppages were generally experienced when exposed to conditions outside the scope of

most of the models (i.e. counterflow, and congestion from floors below). However, in the Japanese study where the occupants had more floors to travel to reach safety, congestion compounded itself over more area. Therefore, introducing counterflow to a taller building may give greater insight into its effects.

The pre-movement time of a population was considered by Proulx. Proulx observed in office buildings, that the pre-evacuation time was between 36 and 63 seconds [2]. A pre-evacuation time was not determined for each individual in this study, but as an estimation and comparison to Proulx's study, the time the first person at each floor level was observed to enter into the stairwell, through the landing door, has been determined. This provides a pre-movement time (including the time required to decide what actions to take) plus travel time for the first person at each floor. Although the first person that entered the landing may have been the individual with the shortest pre-evacuation time and travel time, there is a practical reason for choosing these individuals. In Wing B, as the stairwell became more crowded it was more difficult to identify how many people entered through the landing door because of the poor camera angle; eventually the occupants who entered through the door became a blur. Therefore, in light of this limitation, the first person that entered the stairwell through the doorway was the most clear and is used as an upper estimate of pre-evacuation time. Also, it should be considered that there is a travel time involved in reaching the stairwell that is not generally considered part of the pre-evacuation movement.

For Wing A the average time was 62 seconds for first entry, and in Wing B the average time was 52 seconds (see Table 6.4). Therefore, with the travel time included, this estimate falls within the upper limits of Proulx's findings. However, these values

found for the first person seen in the current study were most likely for the fastest people or those that were closest to the stairwell. Therefore it is stressed that this is an estimate. Since the stairwells are evenly spaced throughout the facility, and there were not generally locations in the building that were inaccessible, it is assumed that it did not take the entire time reported simply to travel to the stairwell.

A more detailed investigation of pre-movement activities for a population is an area for future research that could add to the knowledge that Proulx has determined. Therefore the only conclusions that can be drawn from the comparison between Table 6.4, the amount of people who collected objects, and Proulx's findings is that there is the potential for more complicated pre-evacuation movement than often assumed.

Table 6. 4 Pre-evacuation time plus travel time for 1st person to enter each floor

Floor Level	Wing A: First Person Through Landing Doorway (s)	Wing B: First Person Through Landing Doorway (s)
F2	48	56
F3	54	79
F5	84	22
Average	62	52

Table 6. 5 Summary of comparison results for population flow rate

	Type of Study	Results
Pauls' Effective Width Model	Movement down stairwells.	Results are possible within the assumptions made, but do not agree with the findings of this evacuation.
Pauls' model in SFPE Handbook	Movement down stairwells.	Predicts higher flow rates than actually experienced at the different density levels. Slightly better at predicting movement <i>with</i> counterflow.
Kagawa, Kose, and Morishita's	Movement down Stairwells.	Found similar length stoppages in the stairwell. Provides evidence that current study could be repeated with a taller building.
Proulx	Pre-evacuation time.	Similar estimates of pre-evacuation times.

6.4 Density

As has become clear, much of the literature regards velocity and flow rate as a function of density. This is a reoccurring theme in people movement studies. It is even evident in such opposed flow studies as that conducted by Navin and Wheeler where they varied both density and percent of counterflow. The current study has re-affirmed that density can in fact directly impact the flow rate and the velocity. The only difference in the assumptions made in this study was the idea that density was not the only way to affect speed or flow rate. Other behavioral related factors had an impact, as well as the effects of counterflow. Both in Pauls, and Predtechenskii and Milinskii's models speed and flow are treated as exclusively a function of density, and each other; this is because their assumptions are such that other factors were less significant. The assumption that

such factors as human behavior and response, and counterflow were negligible would have greatly changed the circumstances of this particular evacuation.

Chapter 7: Summary and Future Research

7.1 Introduction

To summarize, quite often population speed, density, and flow rate are the only parameters considered in depth when characterizing the movement of an evacuating population. This study provides an investigation into this fundamental assumption. The effects of the counterflow movement of firefighters that were traveling up the stairwell while an evacuating population was traveling down provided conditions outside this assumption. Also an investigation into the contribution human behavior played in this evacuation was investigated. The effects of these conditions were analyzed both qualitatively and quantitatively. The primary focus of this report were the effects that counterflow had on population speed, density, and flow rate, as well as human behavior as a significant contributor to movement conditions in this particular stairwell evacuation.

7.2 Conclusion

In conclusion, counterflow had a small but noteworthy effect on the capabilities of this population. The higher a person entered the stairwell the more significant the effects became. The speed of the population with counterflow was slower by between 0.1 and 0.3 m/s. Wing B (the wing with counterflow) maintained more dense conditions throughout the duration of the evacuation. When the firefighters entered, the density spiked dramatically and directly after the firefighters left a floor the density dropped. However, even with this decrease, the density never recovered to the conditions experienced in Wing A. The population flow rate of the stairwell overall confirmed this general finding. Coinciding with the entry of the two groups of firefighters, the

population in the stairwell with counterflow was significantly greater (by as much as 36 people). Thus, it is the conclusion of this study that in this six-story office building, counterflow made a noteworthy difference on population speed, density, and flow rate.

Human behavior has been found to significantly impact the outcome of this evacuation. Nonadaptive behaviors, such as occupants traveling back into the building, collisions between occupants, and even unsafe behavior of security guards were noted as having an impact on flow rate and the total evacuation time. Also, 48% of the population brought at least one object with them upon evacuating. Most of these individuals were women (almost 80%), and the object most commonly carried was a purse or briefcase. Thus, it is the conclusion of this study that human behavior impacted the basic egress parameters in this evacuation.

The behavior of the firefighters also impacted the outcome of the evacuation. Firefighters were found to give inconsistent directions to the occupants. When occupants were told to move to the right they formed organized, single file lines in the stairwells. When they were given no directions, or just told to move out of the way, they were disorganized, and often had to contort their bodies to make room for the firefighters.

Another noteworthy behavior observed at the double door exits of the stairwell was that occupants rarely used both sides of the doors simultaneously. They most often followed the person in front of them through the door. In Wing B, this phenomenon was so pronounced that while occupants were exiting exclusively through the left side double door, firefighters attempted to use the same door to enter. This occurred even when the right side of the double door was completely unused.

Simple egress models were used to predict the conditions in the stairwells and were then compared to the actual conditions observed. In a few cases the literature was found to better agree *with* the counterflow stairwell. This includes the speeds predicted using Predtechenskii and Milinskii's model (see Figures 6.1 and 6.2), as well as the observational results from Fruin's study regarding population speed. This finding is most likely because the stairwells in this study were wider than those found in Predtechenskii and Milinskii, and Fruin's studies. Thus, the counterflow essentially narrowed the stairwell for the evacuating population and simulated the conditions experienced in a narrower stairwell with no counterflow.

Kagawa, Kose, and Morishita's observational study had certain similarities to this study including similar length stoppages inside the stairwell. A rough comparison to Proulx's pre-evacuation study indicated that pre-evacuation movement may have been common in this drill. This coupled with the tendency of occupants in this drill to carry items with them almost 50% of the time when they evacuated indicates that this is worth future studies. The two studies available on counterflow both provided comparable findings to this study. Remarkably, counterflow caused the same reduction in speed in the stairwell found in this study as it did in the sidewalk in Holmberg's study. The model based on Pauls' observational data and presented by Proulx proved to not be as strong a predictor of the speeds achieved by this population (see Figures 6.1, 6.2). Also, the prediction of Pauls' Effective Width Model provided idealized values that are not considered to realistic for this evacuation or population.

7.3 Future Research

In order to decrease the effects of counterflow a possible solution is to provide service elevators for firefighters, or exclusive stairwells for firefighter use. An area that needs to be researched is the effect counterflow has in a taller building, or building with narrower stairwells. The height of the building may affect the significance of the role that counterflow plays on the population. Furthermore, a stairwell that is narrower could intensify the effects of counterflow.

Another area of future research is double door usage patterns. If queued occupants are confirmed to primarily use only one side of a double door at a time, as they did in this study, then instructing firefighters to use the opposite door may be a more suitable application of double doors than the current notion that double doors increase occupant flow rate. Since the firefighters in this study consistently decided to travel through the same side of the double doors as the occupants, then it may prove to be of benefit to instruct firefighters to recognize which sides of double doors have queued and if possible travel through the opposite. If this method proves to be effective then it could be used by firefighters for any building with a queued double door with just a moment of inspection.

Also, more general studies on the effects of counterflow, and human behavior in evacuations need to be conducted. This will provide a larger database of information, and a source to incorporate these factors into models. Without an ample and current supply of data it is impossible to create models that accurately predict the conditions of an evacuation.

Appendix

WING A: No Counterflow

* Note: All Directions are taken from the perspective of the individual.

#P	Gender	Description of person	Items Held	Side of body Item held on at F1 double door	Door used at F1 double door	NOTES
1	M	African American, black polo short-sleeved shirt	Paper	L	L	
2	W	African American, long beaded shirt tan in color, black pants	Purse	L	L	
3	W	African American, white long button down shirt, black pants,			L	
4	W	Younger, brown hair in low ponytail, white pants, black button down shirt	small purse	R	L	
5	W	African American, Stocky, tan pants, white shirt	long black purse	L	L	
6	W	Younger, brown hair in low ponytail, gray pants, white button down shirt with white shirt on top.	small purse	R hand	L	
7	W	African American, short hair, white sweater blouse, with gold undershirt, khaki pants	black purse	L	L	
8	W	African American, stocky, ankle length gray shirt with slits, longer white sweater	long black purse	R	L	
9	W	African American, bright pink knee length skirt, pink and black top, gray jacket	pink purse/ small obj in hand	R	L	
10	W	Uniformed, black hat			L	GOING UP: Passes: #P 11 L on F1 dbl doors #P 29 L on F2
11	M	Tall, gray-black pants, white button down shirt, dark tie			L	Turns body to share door with uniformed employee
12	W	Gray and white patterned skirt, white shirt, bright red blazer coat	notebook and to-go coffee	R	L	
13	W	African American, brown blazer and slacks, white undershirt	notebook	R	L	

14	W	African American, maroon pants-suit	notebook	R	L	
15	W	African American, aqua-blue capries, white top, white slip-on shoes, mid-length hair	notebook	L	L	
16	W	Heavy, mid-length brown hair, white shirt with large vertical stripes	notebook	L	L	
17	W	African American, small, black suit dress (short skirt), very short hair	leather notebook	L	L	
18	W	Mid-length brown wavy hair, brown sweater coat, tan blouse, tan pants	Purse to-go coffee	Purse- R to-go coffee- L	L	
19	M	Older, white hair, black pants, white shirt, dark tie			L	
20	W	African American, bright pink shirt, black suit and skirt	tan purse	L	L	
21	W	African American, bright green shirt and capries, bathrobe? Bright blue sneakers			L	
22	W	African American, florescent pink knee length dress, white lacy sweater coat			L	
23	W	Very short hair, black sheer dress with scoop neckline	papers and notebook	R	L	
24	M	Tall, tan suit jacket, gray pants, tie with horizontal stripes, mustache			L	
25	W	African American, aqua-blue suit jacket. Bright pink undershirt, tan skirt with print	paper	L hand	L	
26	M	Slightly large/tall, light blue shirt, gray tie, gray pants.			L	
27	M	Bald, glasses, gray suit and jacket, gray tie			L	
28	M	Tall, tan suit jacket, black pants, mustache			L	
29	M	Younger, medium brown hair, bright red shiny tie, white shirt, brown-gray pants			L	
30	W	Mid-length brown hair, black pants, short-sleeved white button down shirt, with small print	purse	L	L	

31	W	Young, African American, thin, long hair, black pants, white button down shirt, heals	notebook	L	L	
32	W	Short blondish hair, aqua-blue pants, white undershirt, white open shirt, sneakers	pink purse	R	L	
33	W	African American, hair in bun, long white skirt, white shoes, open white shirt, bright pink-red under shirt	purse	R	L	
34	M	Short, gray black hair, black pants, white shirt, dark tie	notebook	R	L	
35	M	Older, tall and hunches over, black baseball hat on, white shirt, black pants, tie			L	
36	M	Young, brown hair, baby blue shirt, tan pants, brown shoes			L	
37	M	Brown hair, youngish, blue shirt, dark gray pants, tie			L	
38	W	African American, brightly patterned tight pants, tan blazer coat	notebook	R	L	
39	W	African American, large frame, bright pink dress, hair in bun	notebook	R	L	
40	M	African American, young, gray pants, white button down shirt, completely bald	briefcase	L	L	
41	W	Purple suit dress, sneakers, longish brown hair			L	
42	W	Short gray-black hair, pink blazer coat, black pants	Papers purse	R	L	
43	W	Mid-length blonde hair, long black dress with small print, tan sweater tied around neck	purse	R	L	
44	W	Young, small, blondish hair in high ponytail, glasses, black pants, white sheer top with white shell	purse	R	L	
46	W	African American, light khaki pants, black shoes, black sweater	purse		L	
47	M	Dark hair, buzzed hair and stubble, white button down shirt, black pants, black shoes	backpack over shoulder	L	L	
48	W	Asian, black button down shirt, light skirt with floral print, black shoes	To-go coffee cup in hand	R	L	

49	W	African American, tall, thin, gray pants, white top, medium length curly hair	notebook	L	L	
50	W	African American, white and gray tiger print button down blouse, gray pants, medium length hair	purse	R	L	
51	M	Balding, medium brown hair, beard	glasses case?	R	L	
52	W	Older, gray-white short hair, gray capris. Pink loose top			L	
53	W	Short brown hair, thin, khaki shirt and pants	red purse	R	L	
54	W	Medium to large frame, bright green dress, blondish hair	black purse	R	L	
55	M	Young, blond, beard, blue shirt, red tie, dark gray pants,	coffee mug	R	L	
56	W	Short brown hair, short, green suit	notebook, purse	L	L	
57	M	Balding, brown hair, comb over, gray pants, dark tie, white shirt			L	
58	W	African American, medium hair, white skirt with black/red tiger print, white shirt	black purse	L	L	
59	M	African American, green satin button-down shirt, dark gray pants	papers	L	L	
60	W	African American, young, hair in a ponytail, bright pink shirt with bright green sweater, tan skirt	shoulderbag	R	L	
61	W	African American, large, long black skirt with big flowers, bright red short-sleeved shirt	purse, cloth	purse- L cloth- R	L	
62	W	African American, large, tight jeans, black sleeveless sweater	purse	L	L	
63	M	Short, red shirt (with white checkers?), khaki pants, brown hair			L	
64	W	African American, young, gray capris. Lime green sweater vest, white button down undershirt	little black purse	R	L	
65	M	Brown hair, young, brown shirt, brown tie, dark pants	papers	R	L	

66	W	Older, short gray hair, white apron, orange undershirt, tan pants, sneakers			L	
67	M	Tall, brown hair, on cell phone! Blue-gray shirt, tie, black pants	talking on cell phone!! note book	cell phone- R note book- L	L	
68	W	Older, short gray-brown hair, long gray dress with print	purse	R	L	
69	W	African American, youngish, white pants, tan shirt with white collar	shoulder bag	L	L	
70	W	African American, young, ponytail, bright yellow long shirt	purse	R	L	
71	W	African American, bright pink shirt, khaki pants, hair pulled back	purse	L	L	
72	W	African American, large frame, teased hair, black pants suit, gray collared undershirt	purse	R	L	
73	M	Blind man's helper. African American, gray shirt, jeans			L	
74	M	Blind man, long cane, darkened glasses, brown hair	shoulderbag	L	L	
75	W	Blondish hair in ponytail, sun glasses, gray and black dress with wild print	two bags	L and R	L	
76	M	African American, tall, young, white shirt (light stripes?), dark gray pants			L	
77	M	African American, tall, young, blue shirt, tie, gray pants			L	
78	W	African American, blondish teased hair, bright pink outfit with floral print			R	**FLOW SWITCHES! (door blocked but people still go through it!) **This woman slows flow down.
79	M	Brown hair, gray suit and coat, reddish tie			R	
80	W	African American, hair in bun, brown suit pants and shirt	To-go coffee cup in hand	L	R	
81	W	Older, aqua-blue dress with black sweater jacket, short brown hair	notebook	L	R	

82	W	Blond mid-length hair, gray blazer coat, black knee length skirt, white shirt	coffee mug notebook	L	R	
83	W	African American, black suit skirt and blazer with white undershirt, hair in low ponytail	purse	L	R	
84	M	African American, white shirt with blue stripes, yellow tie, gray pants, COFFEE CUP	coffee cup papers	L	R	**#P85 and this man COLLIDE in doorway when #p85 switches flows to the L door!
85	M	Grey beard, black cap, black shirt, gray coat, black pants, black shoes			R	**COLLIDES with #P84
86	M	Short, young, green polo shirt, black pants, light brown hair			R	
87	M	Crew cut, glasses on head, orange shirt, white undershirt, light jeans	soda bottle	L	R	
88	W	White visor, gold tank top, white skirt	purse	R	R	
89	M	Blond, sunglasses on, gray shirt, khaki tie, gray pants, brown shoes			L	
90	W	Bright red, pink, and orange striped sweater, green khaki long skirt, mid-length brown hair	purse papers	R	R	
91	M	Light brown suit and coat, red tie	To-go coffee cup in hand	R	L	
92	M	Tall, white shirt, khaki pants, brown shoes, brown hair	coffee mug	L	R	
93	W	Short brown hair, plaid dark green/blue pants, white shirt, black vest	backpack purse	L	R	
94	W	African American, black pants, white sweater set, mid-length hair	purse coat	R	L	
94.5	W	African American, long black dress with white print, white sweater	notebook	L	L	

95	W	Young, dark blonde hair in ponytail, yellow shirt, black pants, yellow shoes	big purse	L	R	
96	W	Tan pants outfit with matching blazer, black undershirt, blondish hair with headband	papers	L	R	
97	W	Gray curly mid-length hair, light gray pants, dark gray top	papers	L	L	
98	M	Brown hair, tall, dark gray shirt, black pants	papers	L	L	
99	W	African American, long bright pink dress	purse	L	L	*Trouble walking **P99 Slows flow
100	W	Short brown hair, bright red shirt, black pants			L	
101	W	African American, bright aqua-blue capris and top, gray hair in bun	shoulderbag	R	L	
102	W	African American, hair braided and pulled back, Long gray coat			L	
103	W	African American, plum pants and top with black undershirt, mid-length hair			L	
104	W	African American, white shirt, gray pants, hair pulled back	purse	L	L	
105	W	Short brown curly hair, black suit and pants, black undershirt with print	papers purse	R	L	
106	W	Curly mid-length hair, black pants and bright pink undershirt	purse	R	L	
107	W	Older, white mid-length hair, white sweater with bright red stripes, blue pants	purse	L	L	
108	W	African American, white undershirt, white open shirt with black print, khaki long skirt	soda bottle	R	L	
109	W	African American, black pants, red shirt with red scarf	coat purse	coat- L purse- R	L	
110	W	Young, tall, blonde hair in bun, green button down shirt, black pants	purse keys	L	L	

111	M	Tall, gray hair, khaki pants, green shirt, tie			L	
112	W	African American, low cut gray patterned shirt, long light blue-white coat, white pants			L	
113	W	Asian, mid-length hair, long black sweater jacket, black pants, purple shirt underneath	papers	R	L	
114	M	Khaki pants, sunglasses on, gray shirt, tie, khaki pants, tie			L	
115	W	African American, blue patterned long dress, very short hair	purse	R	L	
116	W	White suit dress (knee length), short blonde hair	notebook purse	notebook- L purse- R	L	
117	M	White shirt, greenish tie, black pants			L	
118	W	African American, mid-length hair, black pants, black coat with tan fur inside and big collar	purse	R	L	
119	M	White shirt, sleeves rolled up, red tie, khaki pants, holding blue evacuation hat	evac hat in hand	L	L	
120	W	Very light blonde hair pulled back, light blue long dress	pink purse	both	L	
121	W	African American (?), dark hair in bun, khaki green shirt, black pants	purse	R	L	holds door for 4s for #P122
122	W	African American, large, white shirt with bright print, black pants	small bag	L	L	
123	W	African American, white pants, white shirt, white undershirt	purse	L	L	
124	W	African American, very tall, very short hair, black pants, jean jacket, gray and black scarf	purse	L	R	
125	W	Heavy, very short white-gray hair, white t-shirt, black pants,	book purse	book- L purse- R	R	*Trouble walking, looks fatigued **on 2nd floor stairs she tells #P124 to pass her

126	M	Blue jacket and blue baseball hat	BIG backpack	back	R	
127	M	Grey shirt, black pants, brown hair	papers	L	R	
128	W	Red jacket, red purse, white shirt, white pants, hair in low ponytail	Purse	R	L	

WING B: Counterflow

						Note: All Directions are from the perspective of the individual.
#P	Gender	Description of person	Items Held	Side of body Item held on at F1 double door	Door used	Notes at F1 Double Door
1	M	Warden- black hat (uniform), yellow safety vest, black slacks, African American			L	
2	M	Large frame, blue button down shirt, gray slacks, African American, bald.			L	
3	W	Black hair in ponytail, glasses, lanyard around neck, tan blouse, black skirt with white print.	small black object	L	L	
4	M	Fire fighter gp1 (engine company- suppression)- lead firefighter (white helmet),	SCBA- self contained breathing apparatus, flashlight, mask, radio	NA	L	
5	M	Fire fighter gp1 (black helmet)	SCBA, high-rise pack (attack line, fittings, nozzles, etc.), mask, flashlight	NA	L	
6	M	Fire fighter gp1 (black helmet)	SCBA, high-rise pack (attack line, fittings, nozzles, etc.), mask, flash light	NA	L	
7	W	Younger woman, black hair, striped black business shirt, glasses, Asian/Indian	black purse	R	L	
8	M	Tall, medium brown hair, middle aged, gray-blue button down shirt, khaki pants			L	
9	M	Large frame, stocky, brown hair, plaid shirt (red)			L	
10	M	Africa American, white button down shirt with dark stripes, black pants			L	
11	M	Large frame, light button down shirt, glasses			R	

12	M	Dark shirt with black and white trim			L	
13	W	Large frame, pink shirt, light brown/blonde hair	purse	R	L	
14	M	African American, glasses, white shirt, short	paper	L	L	
15	W	Older, blonde/white hair, glasses, open, print shirt with white/green undershirt,	purse	R	L	
16	W	African American, pink suit and skirt	paper and pen	L	L	
17	W	African American, black suit dress, glasses, hair pulled back	PDA?	L	L	
18	M	Bald, dark shirt with white stripe down left arm			L	
19	M	White shirt and tie, black slacks, glasses, blonde/gray hair			L	
20	M	Balding, dark button down shirt, dark pants			L	
21	M	African American, suit and tie	paper packet	R	L	
22	M	Brown hair, medium/large frame, tie			L	
23	M	Large frame, gray hair, polo shirt, gray pants, glasses			L	
24	M	Older, gray hair, glasses (tinted), polo shirt un-tucked			L	
25	M	Large, gray hair, white button down shirt, gray pants			L	
26	M	Bald, blue button down shirt, dark tie with white pattern, khaki pants			L	
27	M	Asian, young, white button down shirt, red tie			L	
28	W	Asian, stocky, short, yellow shirt, mid-length hair			L	
29	M	Tall, plaid shirt (white with blue), crew cut hair, black pants			L	
30	M	Tall, brown hair, light blue shirt, dark tie with light pattern, khaki pants			L	
31	W	Blonde mid-length hair, black button down shirt and skirt? With bright pattern			L	
32	M	Short, gray hair, tan polo shirt			L	
33	M	African American, red tie, white shirt, dark pants			L	
34	W	Younger, long blonde hair, blue open shirt with white undershirt, khaki pants, glasses			L	
35	M	Bald, dark brown hair, white			L	Puts arm out and

		short sleeve shirt, stocky, khaki pants				holds door for 4s while older woman from behind walks through.
36		Older woman, bright blue shirt, short white hair, glasses	purse	R hand, man opens door for her.	L	
37	M	Salt and pepper hair, bald with beard, very large, button down shirt, short stature			L	
38	M	Bald, glasses, white button down shirt, gray-brown pants. Pen in breast pocket.			L	
39	W	Brown sweater vest, white turtleneck, very short brown hair			L	
40	M	Brown hair crew cut, white shirt, dark tie.			L	FLOW SWITCH! Man moves right once out the door to avoid first fire fighter-- this switches flow.
41	M	Orange polo shirt, crew cut, black lanyard around neck, khaki pants, glasses	to-go coffee cup	R hand	R	stops to look at fire fighter
42	M	Firefighter gp2 (truck company)- lead firefighter (white helmet)	SCBA, flashlight, mask, radio	NA	L	
43	W	African American, short hair in braids, light blue shirt, black coat, glasses hanging round neck	purse	R shoulder	R	
44	M	African American, large frame, maroon shirt with white stripes, glasses			R	turns sideways to go through door at same time as fire fighter
45	M	Firefighter gp2 (truck company)- black helmet	SCBA, flashlight, mask, radio, axe		L	
46	W	Stocky, white shirt, black coat, sunglasses, short brown hair.			R	
47	W	Indian, younger, yellow and black pattern shirt, glasses, long black hair, black jacket	black bag	R shoulder	R	door held for her by man behind her
48	M	Firefighter gp2 (truck company)- African American, black helmet	SCBA, flashlight, mask, radio	NA	L	
49	M	Indian? Dark hair, shorter, dark purple button down shirt, dark tie			R	
50	M	Younger, light blue shirt, tie, coffee mug (to-go), balding, light hair, glasses			R	
51	W	African American, black sleeveless collared top, short hair			R	
52	M	Large, yellowish-white polo shirt with stripes, dark gray hair			L	

53	M	White shirt dark tie, brown hair			R	
54	M	Pink shirt, tie, dark hair			R	
55	W	Long brown hair, young, pink sweater, white shirt.			R	
56	W	White collared shirt, mid-length brown hair with bangs, black lanyard around neck	dark blue jacket	L hand	R	
57	W	African American, black and gray striped blouse, black jacket	purse	L shoulder	R	
58	W	African American, short hair, glasses, large frame, off-white shirt	two bags	One on R shoulder, other on L with hand holding strap.	R	
59	M	African American, white shirt with greenish-gray tie.	coffe to-go cup. No lid		R	
60	M	Maroon polo shirt, large frame, glasses			R	
61	M	African American, large frame, lanyard around neck, tan/greenish button down shirt, dark pants			R	
62	M	Indian? Short-sleeve white polo shirt with white undershirt			R	
63	M	Asian, younger, large frame, dark blue polo shirt, khakis, glasses			R	
64	W	Small, light brown medium-long hair, white sweater-shirt, black pants	purse	R side	R	
65	M	White button-down short-sleeve shirt, dark pants			R	
66	M	African American, button down shirt with vertical stripes, dark pants, glasses, slender frame	newspaper?	L hand	R	
67	W	Long purple casual dress, brown wavy hair	purse	L shoulder	R	
68	M	Grey-black hair, tall, black polo shirt, gray-green khakis	to-go coffee cup	L hand	R	
69	W	Indian, younger, long curly hair, white short-sleeve shirt, glasses, jeans?	purse	R shoulder	R	
70	M	White button down shirt (plaid with light blue lines), khaki pants, large frame, bald on the top of his head			R	
71	W	African American, pink tight t-shirt, large frame, hair in ponytail, jeans	purse	L shoulder	R	

72	W	Asian, small, gray suit, mid-length hair, glasses			R	holds door for the next woman (2s)
73	W	African American, very short hair, glasses, yellow suit coat with black trim, black shirt, black pants.	multiple folders	L hand	R	woman before her holds door
74	M	African American, tall, white mock-turtle neck, brown/khaki pants			R	
75	W	African American, thin, white sheer sweater with white tank top underneath, jeans, mid-length hair	purse	L shoulder	R	
76	M	Gray hair, white shirt, dark tie, black obj in breast pocket, black pants			R	
77	M	Tall, dark button down shirt, glasses, brown hair	bag	L hand	R	
78	W	Brown curly hair pulled back, stocky, white button down shirt, blue skirt	binder	R hand	R	uses opposite hand to open door
79	W	Stocky, blue button down shirt, wearing sunglasses, mid-length brown hair pulled half-up			R	
80	W	Young, blonde, mid-length/long hair, pink button down shirt, black pants	object	L hand	R	
81	M	Bald, whitish button down shirt, tie			R	
82	W	Blonde, young, white short sleeve polo t-shirt, black skirt with white floral print			R	
83	W	Brown hair pulled back, gray suit	soda can	L hand	R	
84	M	Asian, thin, red button down shirt, gray pants	papers, and a can/jar	L hand	R	
85	M	Brown hair, white button down shirt, khaki pants, black lanyard around neck			R	holds door for next man for 4s
86	M	Black suit, white and red striped tie, white shirt, glasses, balding, gray hair			R	
87	M	White-light blue shirt, younger, brown hair, khaki pants			R	
88	M	Short, blondish hair, white button down shirt, khaki pants			R	
89	W	Short brown hair, black sports jacket, white button down shirt, dark pants			R	
90	M	Younger, black hair in crew cut, pink button down shirt, dark framed glasses			R	

91	W	Young, red-brown mid-length hair, dark purple outfit, glasses			R	
92	W	Gray hair, large, white shirt with a print gray shirt over top (open),	purse	R shoulder	R	
93	M	Gray-brown beard, dark brown hair, white shirt, dark tie, dark pants			L	FLOW SWITCH!
94	W	African American, long white dress with dark jacket over, hair pulled back tightly in low ponytail	papers	L hand	L	
95	W	African American, young, dark jacket, dark top, white pants, VERY short hair	big purse to-go coffee	L shoulder (purse) R hand (coffee)	L	
96	M	African American, tall, gray suit (big on him), black shirt with no tie			L	
97	M	African American, bald on top (hair longer on sides), short and stocky, off white polo shirt, khaki pants, lanyard around neck			L	
98	W	Brown mid-length hair, aqua-blue dress with collar and buttons at top			L	
99	M	Short, crew-cut, balding, white button down shirt, light tie, sleeves rolled up, dark pants	can newspaper	R hand (can) L hand (newspaper)	L	
100	M	Large and BIG/tall, Indian?, light blue button down shirt, black-gray pants, gray hair, lanyard around neck			L	
101	M	Asian, short and small, maroon button down shirt, gray pants, yellow bracelet	sunglasses	R hand	L	
102	W	Asian, small, black skirt, floral printed shirt (red/black/some green), mid-length hair	purse	R shoulder	L	
103	W	Larger, white shirt with dark blue suit coat and dark blue suit skirt, long blondish hair	purse (black, large)	R shoulder (with hand also holding)	L	
104	W	African American, very large, button down top gray at top and black at bottom, hair pulled back	purse	L shoulder	L	
105	M	Red button down shirt, striped tie, khaki pants, blonde hair			L	
106	W	Asian, short curly hair, white button down shirt with black trim	Purse binder	L shoulder (purse) R hand (binder)	L	
107	M	Asian, crew cut, off white button down shirt, khaki pants with black belt			L	

108	W	Short, blondish hair, bright pink suit and suit skirt			L	
109	M	Very tall, shaved head, white shirt with thin blue plaid stripes, khaki pants			L	
110	W	Short blonde hair, bright striped sweater (blue white green yellow), yellow pants			L	
111	M	Younger, balding with crew-cut brown hair, short-sleeve gray button down shirt, black pants			L	
112	W	Younger, very big, bright pink sweater (v-neck), dark blonde mid-length hair	purse	R shoulder	L	
113	M	Gray pants, white button down shirt, striped tie, gray-black curly hair			L	
114	W	Brown button down shirt open, black undershirt, black pants, brown short hair			L	
115	W	African American, long white coat with tan vertical stripes, short hair	purse	R shoulder	L	
116	W	Large short, brightly patterned button down shirt, short gray-black hair, glasses			L	
117	W	Asian, ponytail, young, small, white sweater buttoned at top, black undershirt	black coat	R hand	L	
118	M	Crew cut brown hair, tall, white button down shirt, gray pants			L	
119	M	Crew cut gray-black hair, dark sweater with dark button down shirt collar sticking out			L	
120	M	Tall and thin, brown thinning hair, white button down shirt, light tie	backpack	R shoulder	L	
121	W	Young, brown hair in ponytail, black v-neck top, very bright white and black striped skirt	small purse	L shoulder	L	
122	W	Long brown wavy hair pulled half back, yellow shirt, tan pants	coat and purse??	L hand/arm	L	
123	M	Balding, glasses, blond hair, gray short sleeve button down shirt, gray tie, khaki pants	backpack	R shoulder	L	
124	M	Black hair, gray-black beard, dark gray shirt and tie, black pants			L	
125	W	Young, large frame, bright blue t-shirt, gray pants, long brown hair in low ponytail	backpack	both shoulders	L	

126	M	Short, tan baseball cap, gray button down shirt, gray tie, gray pants			L	
127	M	Dark wavy hair, white button down shirt, yellow tie, khaki pants			L	
128	M	African American, tall, gray shirt, gray pants, glasses			L	
129	W	African American, large frame, brownish-red long collared shirt, white undershirt, glasses, hair in bun	Tissue?small piece of paper?	R hand	L	
130	M	Very tall and thin, black crew cut hair, gold glasses, white button down shirt, dark thin tie	Binder	L hand	L	
131	M	Older, gray hair, dark tie, white button down shirt, black pants	Coat backpack	L hand (coat) R shoulder (backpack)	L	
132	M	White button down shirt, dark tie with light dots, dark pants, glasses, thin brown hair			L	
133	M	Bald on top brown hair on sides, light short-sleeved button down shirt, tie, khaki pants, glasses			L	
134	M	Younger, black baseball hat with white trim, white button down shirt, tie			L	
135	M	Very tall, brown hair, gray suit, white shirt, tie			L	
136	M	Floor warden, blue baseball hat, short, white button down shirt with tan vertical stripes, tie, khaki pants			L	
137	M	Blue button down shirt, patterned tie, khaki pants, glasses			L	
138	M	White hair crew cut, white button down shirt, dark pants			L	
139	M	Bright blue button down shirt, tie, gray pants, gray hair, gray beard, glasses			L	
140	M	Large, white buttoned down shirt, red tie, dark pants, dark parted hair			L	
141	M	Floor warden, blue baseball hat, red button down shirt, patterned tie, dark pants			L	
142	M	Floor warden, blue baseball hat, tall and thin, white button down shirt, dark tie, dark pants, glasses			L	
143	M	White button down shirt, sleeves rolled up, black tie, black pants, tall, blonde longish hair			L	

144	M	Asian, small, older, balding, glasses, striped button down white shirt, tie, dark pants			L	
145	M	Floor Warden, blue baseball hat, khaki pants, short-sleeved khaki shirt, glasses, dark hair			L	
146	W	Floor warden, blue baseball hat, blonde hair pulled back, green button down shirt with matching pants	White purse	L shoulder	L	stops to talk in the hallway (3s)
147	M	Floor warden, red baseball hat, white hair, gray shirt, tie, black pants			L	

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